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JET PROPULSION

Journal of the
AMERICAN ROCKET SOCIETY
Rocketry . . . . Jet Propulsion Sciences . . . . Astronautics

VOLUME 26 DECEMBER 1956 NUMBER 12

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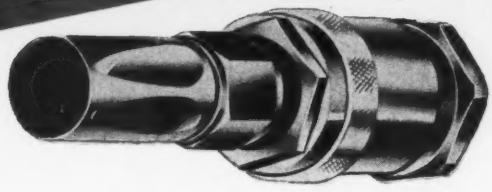

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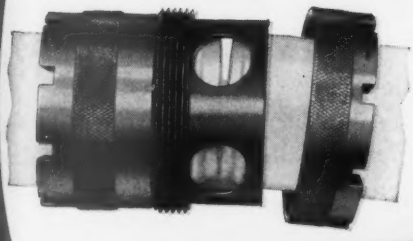

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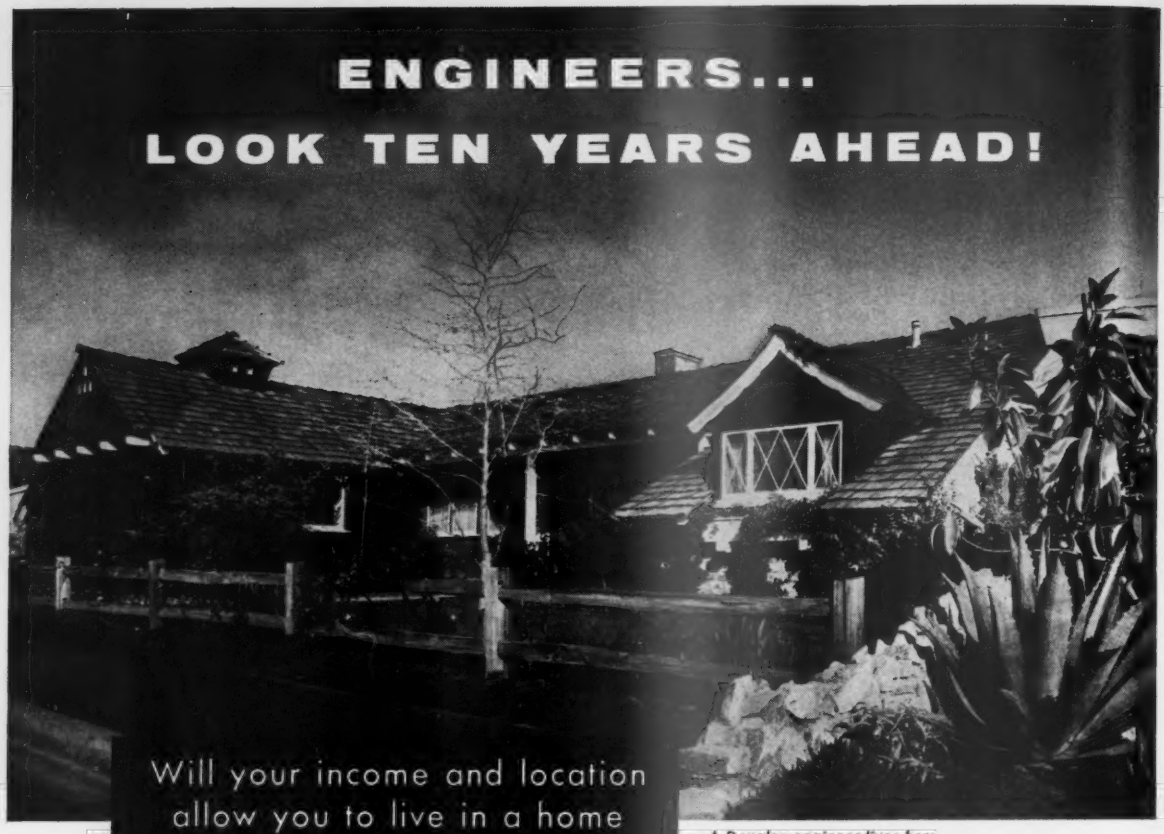

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JET PROPULSION, the Journal of the American Rocket Society, is devoted to the advancement of the field of jet propulsion through the publication of original papers disclosing new knowledge and new developments. The term "jet propulsion" as used herein is understood to embrace all engines that develop thrust by rearward discharge of a jet through a nozzle or duct; and thus it includes systems utilizing atmospheric air and underwater systems, as well as rocket engines. JET PROPULSION is open to contributions, either fundamental or applied, dealing with specialized aspects of jet and rocket propulsion, such as fuels and propellants, combustion, heat transfer, high temperature materials, mechanical design analyses, flight mechanics of jet-propelled vehicles, astronautics, and so forth. JET PROPULSION endeavors, also, to keep its subscribers informed of the affairs of the Society and of outstanding events in the rocket and jet propulsion field.

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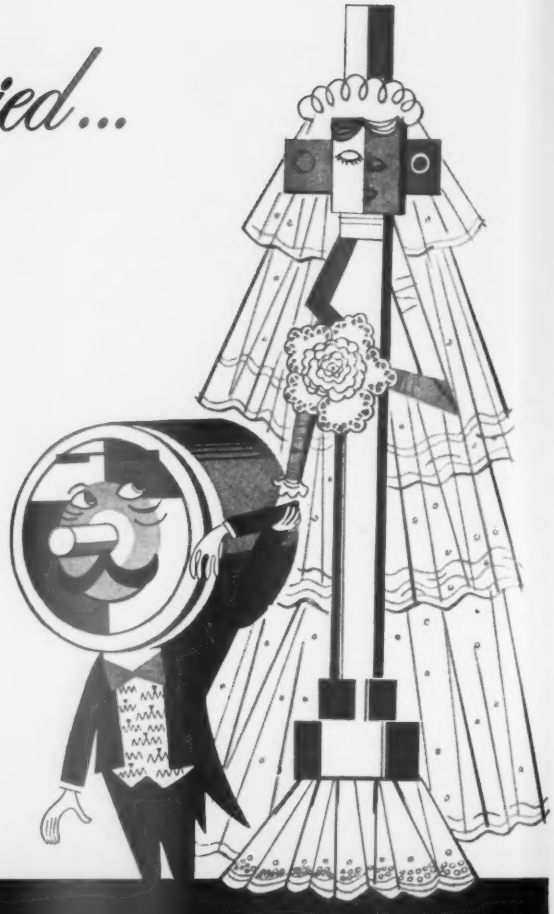
Just Married...

In an unusual setting in the laboratories of G. M. Giannini & Co., Inc., Miss Hydraulic Actuator and Mr. Precision Potentiometer recently were united at ceremonies attended by leading engineers and scientists. Solicitous friends have long awaited this happy union ...the couple, known to their intimates as Ac-pot, soon will reside in the most advanced control systems being developed.



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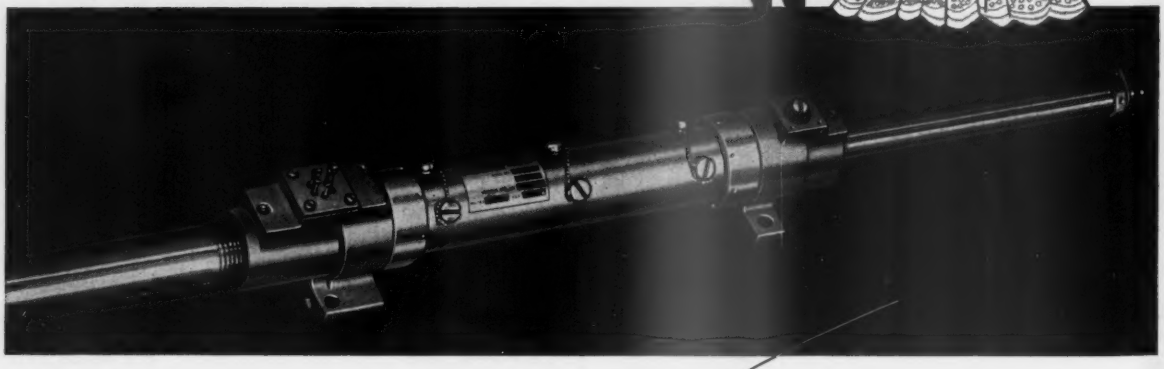

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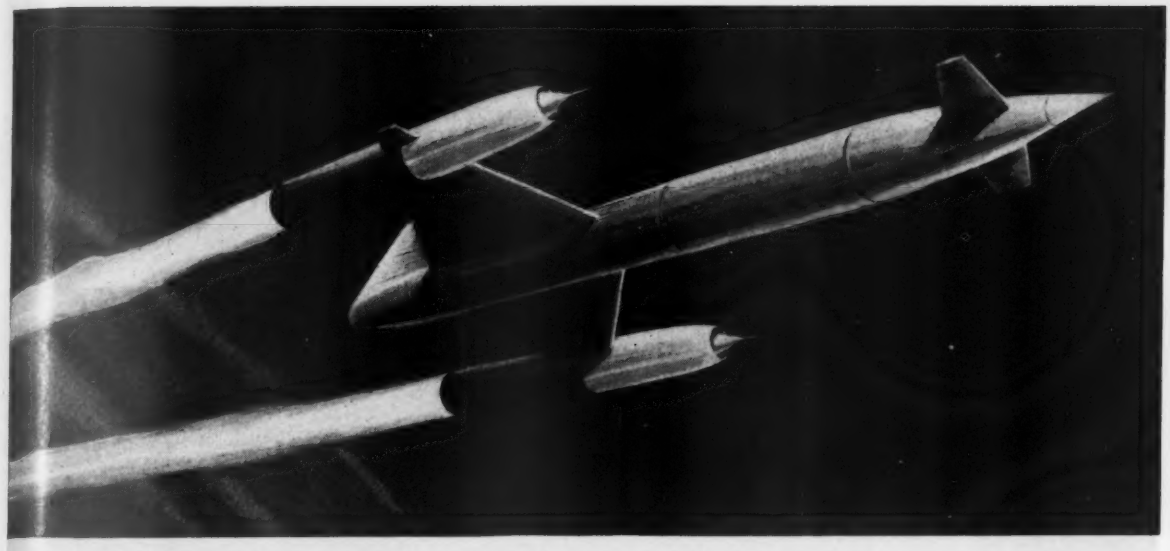
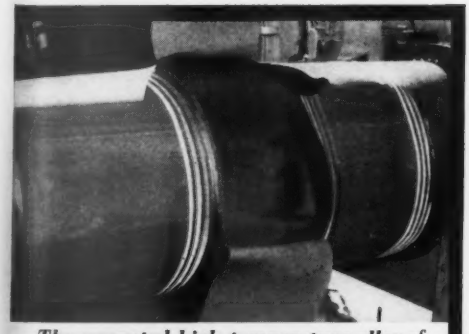


New, highly advanced ramjet engines **designed and built by Marquardt Aircraft Company of Van Nuys, California, for supersonic missiles use Norton Rokide "A" spray coating. The Rokide coating aids in assuring successful flight by greatly increasing the resistance of the tailpipe to excessive heat and abrasion.**

Norton ROKIDE* coating plays vital role in Supersonic missiles



The uncoated high temperature alloy **of this ramjet engine tailpipe failed during an especially severe testing in 14.2 seconds. Metal temperature exceeded 2200°F.**

Coated with Rokide "A" **on the forward portion only, an identical tailpipe was tested for 18.3 seconds without failure. Maximum metal temperature was 1800°F.**

ROKIDE "A" aluminum oxide coating is one of three Norton refractory spray coatings — including ROKIDE "ZS" zirconium silicate and ROKIDE "Z" stabilized zirconia — now being widely used in modern high temperature applications.

In reaction motors and in various AEC projects, for example, the high melting point and low thermal conductivity of ROKIDE "A" coating reduces the temperature of the underlying material and permits higher operation temperatures. It is both thermally and electrically insulating, and its hardness, chemical inertness and stability in combustion temperature provide high resistance to excessive heat, abrasion, erosion and corrosion.

ROKIDE "A" Coating vs. Stainless Steel

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ROKIDE coatings are applied in molten state by a metallizing spray gun. Coatings may be applied to parts of all sizes and shapes accessible to the spray gun equipment. Licenses for the use of the ROKIDE coating process can be obtained from Norton Company. For further facts on ROKIDE coatings — and for aid in problems involving high temperature materials — write, mentioning your requirements, to NORTON COMPANY, Refractories Division, 643 New Bond Street, Worcester 6, Mass.

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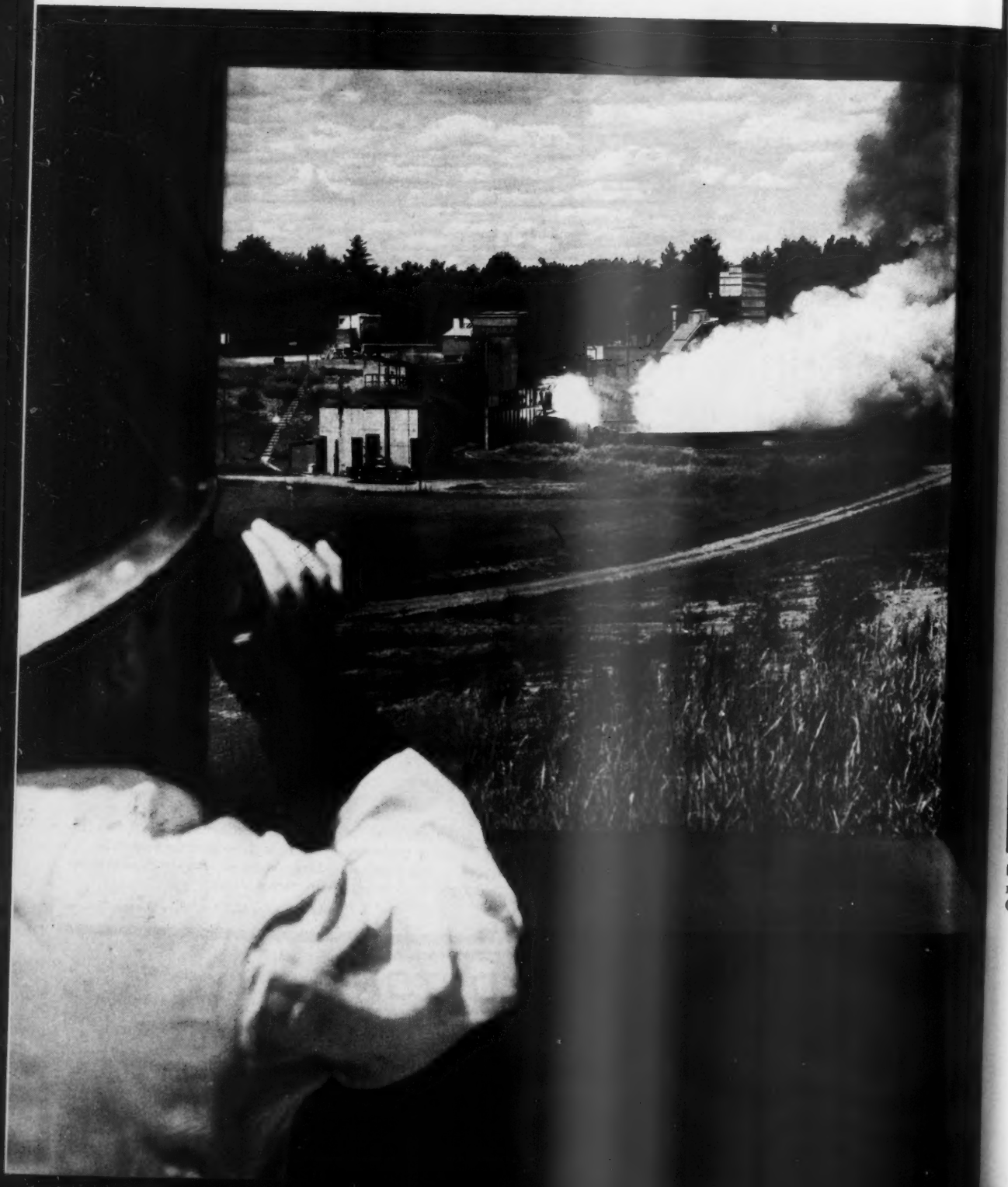
PROGRESS REPORT ON PROJECT VANGUARD

General Electric X405 Being R



ngReadied For Flight Testing

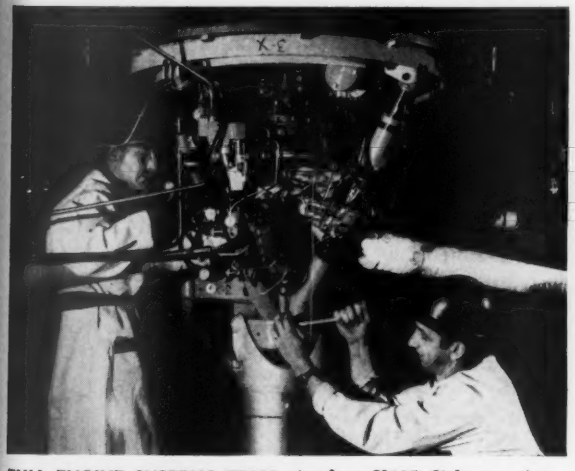
"Flyable" model of G-E rocket engine on schedule at fully instrumented Malta, N. Y. rocket test station

General Electric's new X405 rocket engine has already completed many successful static test runs—only a year after General Electric was awarded a contract to build the first-stage powerplant for the VANGUARD rocket. Now being qualified for flight test, the G-E X405 is scheduled for early delivery to Martin-Baltimore, builder of the VANGUARD airframe and prime contractor for the earth satellite launch vehicle.

When the bi-liquid X405 launches the finless, three-stage VANGUARD rocket during the International Geophysical Year, it will produce more than 27,000 pounds of thrust and have a burning time of about 150 seconds. At burnout 36 miles above the earth, the X405 rocket engine will have accelerated the VANGUARD rocket to a speed of 4000 mph—more than a mile a second!

The advanced G-E powerplant is currently undergoing detailed qualification testing at the Malta, N. Y. rocket test station, operated by General Electric for the U. S. government. Fully instrumented, Malta's advanced engine and component testing facilities have enabled G-E rocket engineers to make rapid progress in the development of the X405.

Superior performance of G.E.'s X405 is the result of more than a decade of General Electric rocket engine experience. The new powerplant marks another milestone in G-E rocket engine progress, is another example of how General Electric today can provide the U. S. rocket and missile industry with highly reliable, high performance rocket engines . . . of unmatched quality. ***General Electric Company, Cincinnati 15, Ohio.*** 234-9



FULL ENGINE SYSTEMS TESTS simulate X405 flight requirements, duration of actual VANGUARD first-stage run. Above, G-E technicians install X405 engine in rocket test pit in Malta.

X405 ENGINE RUNS ARE CONTROLLED from blockhouse, adjacent to firing pit. Completely instrumented test cells record continuous performance data during close-to 150-second run.

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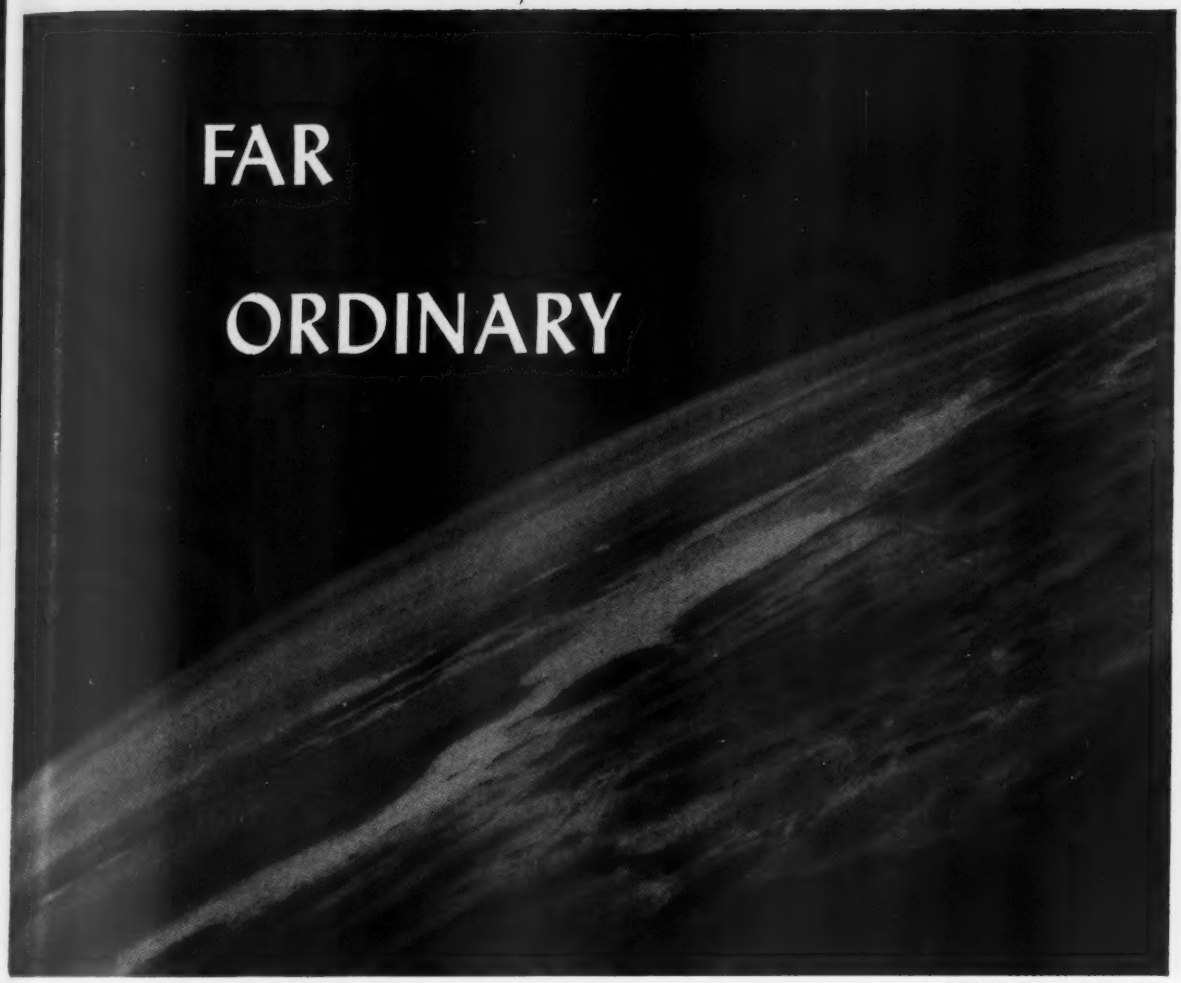

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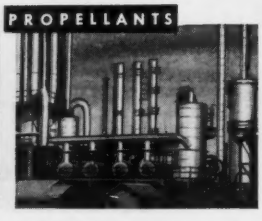

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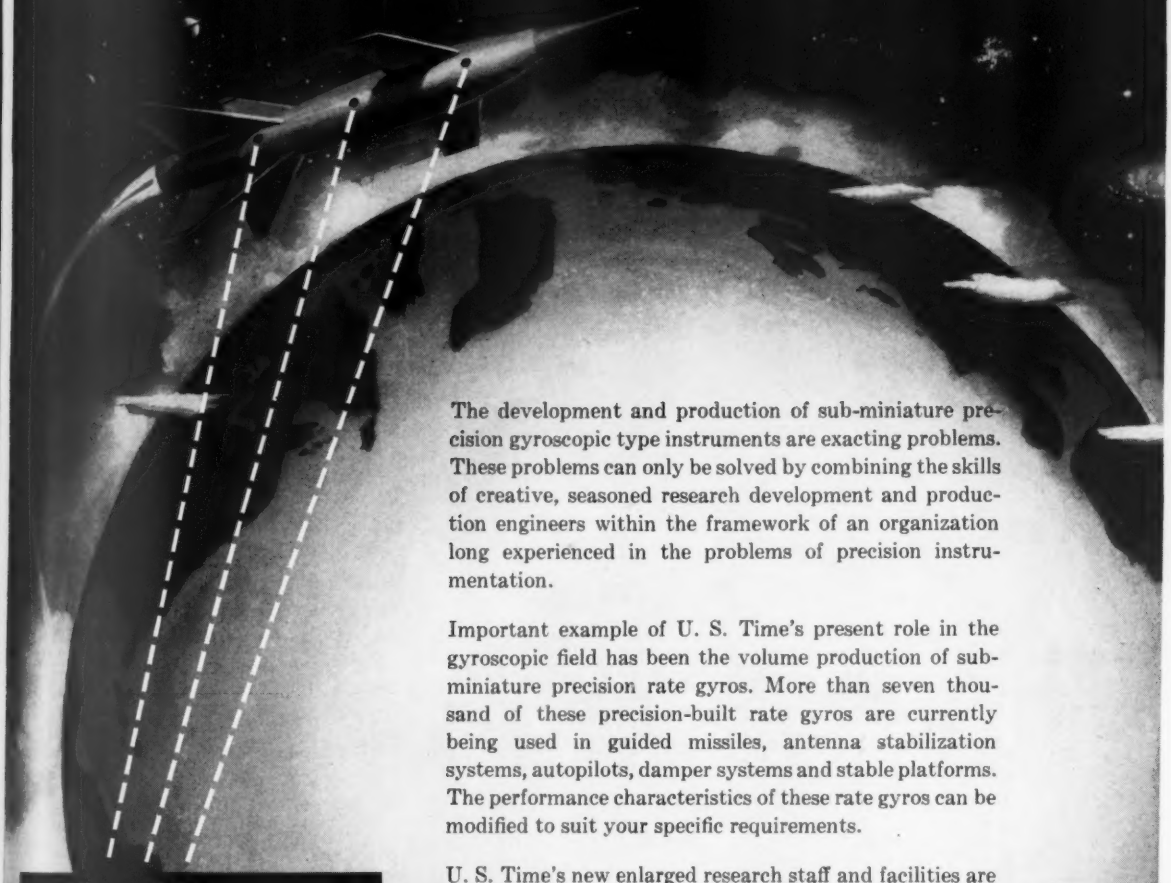

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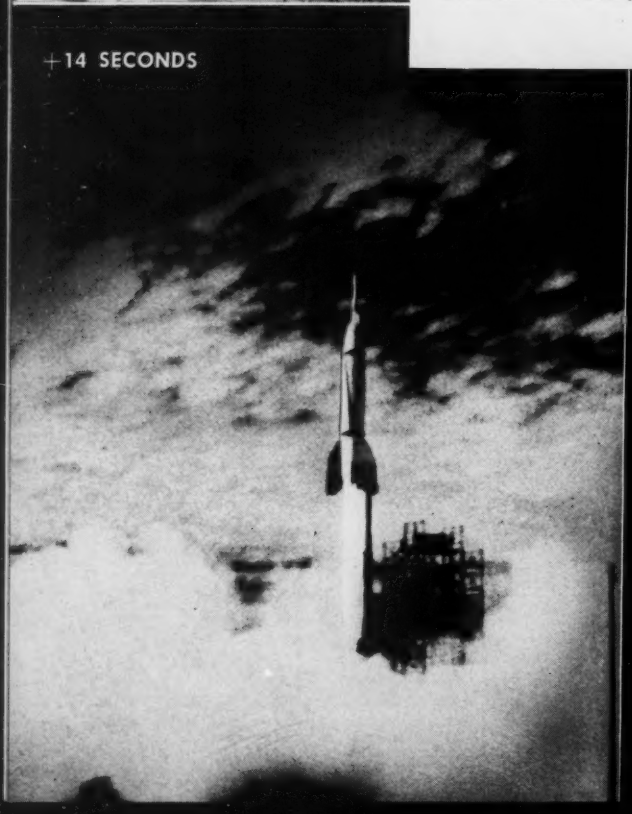

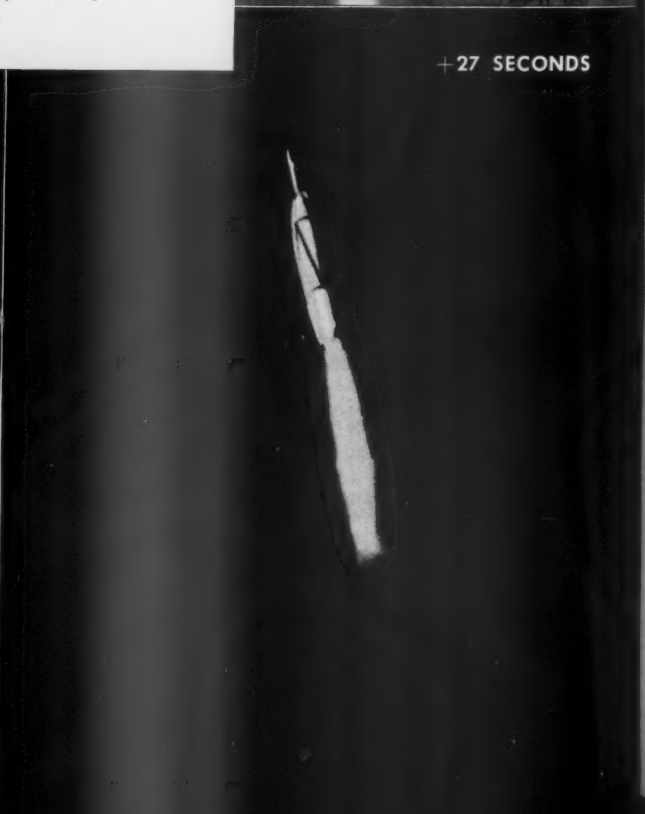

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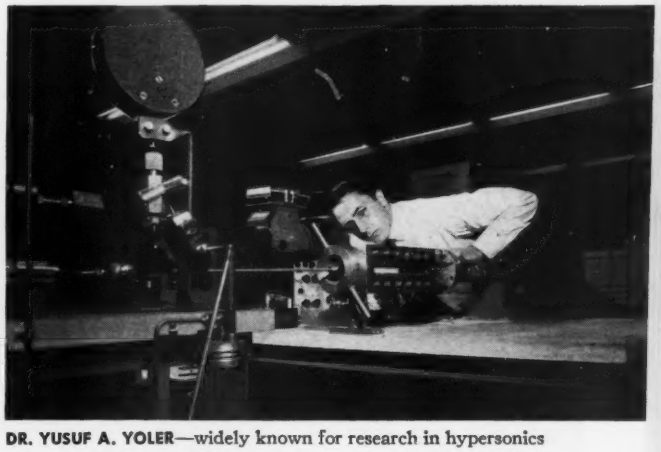

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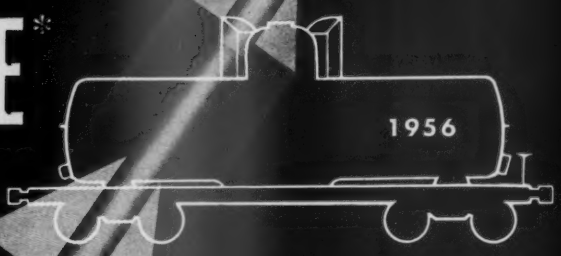

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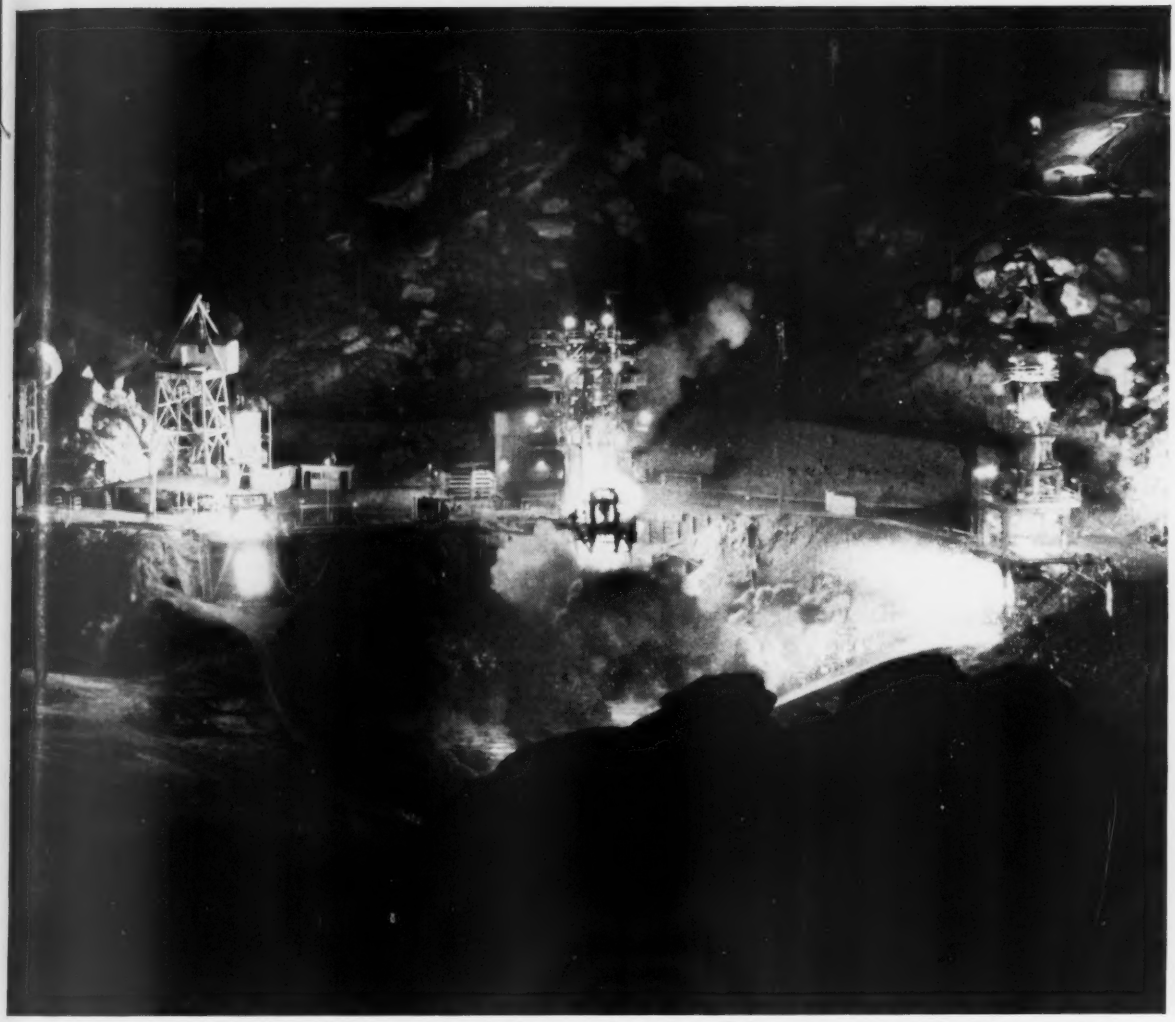

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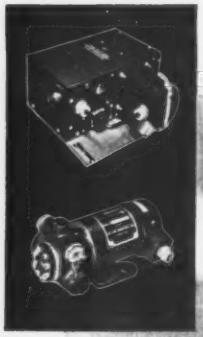

Aviation Catalog 340, on request.

Eastern INDUSTRIES, INC.

100 Skiff St., Hamden, Conn.

DECEMBER 1956

VOLUME 26 NUMBER 12

JET PROPULSION
Journal of the
AMERICAN ROCKET SOCIETY

Editor-in-Chief

MARTIN SUMMERFIELD

The Effect of Meteoric Particles on a Satellite

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Erosion effects of high velocity meteoric dust on space vehicles are of great importance but not easily predictable. This paper discusses some physical models to allow calculations of the erosion rate; they lead to widely differing values. Laboratory experiments with artificially accelerated dust particles should furnish more reliable guides for a theory. Even so, important indications are derived for the choice of material and construction of a satellite skin to minimize meteor effects. Atmospheric sputtering is shown to be unimportant, e.g., in the case of an aluminum skin. An erosion experiment for the Vanguard satellite is described. It is based on a radioactive method which has many advantages in terms of sensitivity and simplicity. The results can be used to study the effect of the sun on dust particles in interplanetary space.

Introduction

FOR space flight and for satellites, meteors represent one of the greatest hazards. Of all of the incident radiations and particles, meteors contain the largest individual amounts of energy. As seen from Table 1, meteor energies range from 10^{13} ergs down to 10^{7}. Micrometeors are too small to produce luminous trails and have lower energies; but recalling that 1 erg = 1.6×10^{12} ev, we realize that micrometeors have kinetic energies far exceeding the kinetic energy of the average cosmic ray which is only 10 billion ev. Although cosmic rays can have energies ranging up to 10^{17} ev, their effect on matter is much different from that of meteors. The difference arises, of course, due to the vastly different mass, the mass of a cosmic ray being that of an atomic nucleus, while the smallest micrometeor contains of the order of 10^{10} to 10^{13} atomic nuclei. The meteors have, therefore, a correspondingly small velocity, while cosmic rays move with nearly the velocity of light. This difference in velocity implies a difference in interactions with solid material. For example, a cosmic ray will penetrate easily large thicknesses of material and in general will lose only small amounts of energy, of the order of 2 million ev in penetrating 1 gm/cm² of material (1, 2, 3).[2] Most of this energy is given to the electrons in a metal while the lattice structure of the metal itself is not disturbed. These effects, of course, are self-healing because of the high conductivity of the metal. On the other hand, plastics or organic materials having complicated molecules will suffer due to prolonged cosmic ray bombardment. Also, cosmic rays can disintegrate nuclei and thus produce permanent effects (4).

Meteors, however, because of their low velocities, typically around 50 kmps, will penetrate only a small distance and must of necessity *give up all of their energy in this small distance.* Their specific effects, therefore, are very much greater than those of cosmic rays.

Penetration by Large Meteors

The effects of large meteors, those having a mass of more than a microgram, will be to penetrate thin skins of satellites

Presented at the ARS Semi-Annual Meeting, Cleveland, Ohio, June 18–20, 1956.

[1] Associate Professor of Physics. Mem. ARS.

[2] Numbers in parentheses indicate References at end of paper.

Table 1. Data concerning meteoroids and their penetrating probabilities[1]

Meteor visual magnitude	Total kinetic energy, ergs	Mass, gram	Radius, cm	Prob. encounter[2] per 24 hr	Penetration in Al, cm
0	1.0×10^{13}	1.25	0.46	1.2×10^{-6}	10.9
1	4.0×10^{12}	0.50	0.34	3.1×10^{-6}	8.0
2	1.6×10^{12}	1.98×10^{-1}	0.25	7.7×10^{-6}	5.9
3	6.3×10^{11}	7.9×10^{-2}	0.18	2.0×10^{-7}	4.3
4	2.5×10^{11}	3.1×10^{-2}	0.14	4.9×10^{-7}	3.2
5	1.0×10^{11}	1.2×10^{-2}	1.0×10^{-1}	1.2×10^{-6}	2.3
6	4.0×10^{10}	5.0×10^{-3}	7.4×10^{-2}	3.1×10^{-6}	1.7
7	1.6×10^{10}	2.0×10^{-3}	5.4×10^{-2}	7.7×10^{-6}	1.3
8	6.3×10^{9}	7.9×10^{-4}	4.0×10^{-2}	2.0×10^{-5}	0.93
9	2.5×10^{9}	3.1×10^{-4}	2.9×10^{-2}	4.9×10^{-5}	0.69
10	1.0×10^{9}	1.2×10^{-4}	2.2×10^{-2}	1.2×10^{-4}	0.51
11	4.0×10^{8}	5.0×10^{-5}	1.6×10^{-2}	3.1×10^{-4}	0.37
12	1.6×10^{8}	2.0×10^{-5}	1.2×10^{-2}	7.7×10^{-4}	0.27
13	6.3×10^{7}	7.9×10^{-6}	8.6×10^{-3}	2.0×10^{-3}	0.20
14	2.5×10^{7}	3.1×10^{-6}	6.3×10^{-3}	4.9×10^{-3}	0.15
15	1.0×10^{7}	1.2×10^{-6}	4.6×10^{-3}	1.2×10^{-2}	0.11

[1] From Reference (7).

[2] For a sphere of 3-m diam.

or space ships upon impact—a microgram meteor penetrating approximately one millimeter of aluminum skin (5, 6, 7). On the other hand, the much smaller and less energetic micrometeorites will not be able to penetrate a skin of this thickness but instead will gouge out small pieces of the skin, a process which is very similar to sandblasting. Prolonged exposure above the atmosphere, therefore, will produce a gradual erosion of the skin; this thinning has deleterious effects since it will eventually damage the integrity of the space ship or satellite.

Table 1, taken from (7), represents our best present thinking on the frequency of meteors of a given size and on their ability to penetrate the skin of a satellite. The theory of penetration of meteors is largely based on the original work of Öpik (8) and has been modified by Grimminger (5) and Whipple (7). Whipple's paper, particularly, contains an excellent review of our knowledge of meteoric phenomena. The present paper can add little to the pioneer work of Grimminger, Öpik, and Whipple; it will be devoted therefore to the discussion of the *erosion* effects of the *very small* meteoric particles (micrometeors or interplanetary dust).

Calculation of Meteoric Erosion

The problem is a threefold one. It is first necessary to derive the flux of micrometeors of different masses and different energies at the top of the atmosphere. This flux is given by the space concentration times the velocity of the particles. The data rest entirely on astronomical observations, such as observations of scattering of sunlight by interplanetary dust (which causes the solar dust corona and the zodiacal light), on observations of impacts of dust particles in high altitude rockets, and on measurements of the accretion of such material by the earth through the study of ocean bottom deposits. Whipple (7) has reviewed the evidence and gives an accretion of 1000 tons of meteoric material per day. (A reevaluation of the data may, however, lead to an accretion rate as small as 20 tons per day (9). As we shall see later, uncertainty in the flux is minor compared to the lack of knowledge of the effect of particles impacting at high velocities.

(i) For the present calculation we will assume an incident flux of 200 tons per day at a velocity of 50 kmps. The incoming kinetic energy, therefore, is about 5×10^{-6} w/m^2 or 6×10^{13} ev per m^2 per sec. (For comparison, the energy input from the sun is 1400 w/m^2.)

(ii) The second step is to get information on the effect of the impact of a single high speed (50 kmps) particle on a metal surface. Such data are not available at present; however, as discussed later, they could be studied in the laboratory by accelerating particles to these high speeds and observing their impacts.

(iii) Finally, it is necessary to combine the data from the two sources in order to calculate the integrated erosion effect of dust bombardment on the skin of the satellite.

Consideration of Various Theoretical Models

In the absence of any data on the effects of dust particle impacts and in the absence of any detailed theory of the effect, we must set up some simple models and investigate their consequences.

Moving with a speed of at least 10 kmps (probably more of the order 30–50 kmps), the kinetic energy per atom in the dust particle is of the order of 100 and up to 500 ev. In comparison to this value we can neglect the binding energy between atoms whose maximum value is given by the sublimation energy, approximately 2 to 9 ev for most materials. We can, therefore, consider the meteor penetrating into the metal surface as if it were a liquid until the meteor atoms have lost enough energy to be in the range of binding energies of the metal lattice.

Model A. Sputtering: One extreme assumption in calculating the mass loss from the satellite skin is to consider the meteor made up of individual atoms and calculate the sputtering to be expected from this collection of atoms which make up the meteor. This calculation is carried out using the data on sputtering thresholds and sputtering yields given by Wehner (10). The incidence of 200 tons of meteoric dust over the earth's surface per day brings in 4×10^{30} atoms (assuming an atomic weight of 30) or 10^{11} atoms per m^2 per sec. The energy per atom is taken as 420 ev. If we choose an aluminum skin (threshold 125 v), the sputtering yield is $\sim$1 for a variety of experimental conditions. The number of atoms sputtered off the skin per m^2 per sec is therefore about 10^{11}. Now 1 m^3 of Al weighs 2700 kg and contains 6×10^{28} atoms. To sputter off a uniform layer 10 μ thick would therefore require 6×10^{12} sec or 200,000 years.

This calculation gives an extremely small mass loss but it is certainly *not realistic* since it neglects the cooperative effects of the meteor atoms. One important result, however, stemming from this calculation is the realization that one should construct the satellite with a material having as high a sputtering threshold as possible. Aluminum with a threshold of about 125 v is well suited for the purpose; so is titanium. Metals to avoid would be lead, antimony, silver, and gold, all of them having a threshold below 50 v. (See later discussion on collision with gas atoms.)

Model B. Sublimation: If we consider the cooperative effects of the meteor atoms, we take into account that a large number of them arrive within the period of vibration of the metal lattice. If we take this vibrational period of the order of 10^{-13} sec, we find that the energy input in this time over an area of 1 sq Ångstrom is about 4000 ev. As a second model, therefore, we will assume that all of the energy of the meteor is used in sublimating atoms from the skin of the satellite. If we take the sublimation energy of the order of 3 ev for aluminum, or 5 ev for titanium, we get the results given below:

The incident energy is 6×10^{13} ev per m^2 per sec. The number of Al atoms sublimated off the surface is 2×10^{13} per m^2 per sec. To sublimate off a thickness of 10 μ would require 3×10^{10} sec, or about 1000 years.

Again we see that the erosion rate of the skin is extremely small and hardly measurable. But again this calculation may not be realistic because we have assumed that each atom of the skin is separately removed.

Model C: From sandblasting experiments we know that the metal is chipped off in fine dust particles. The size of these dust particles is not known as a function of the size and velocity of the bombarding dust. However, in order to make an estimate we shall assume that the size of the metal dust produced by the bombardment is of the order of 10 μ in linear dimension, comparable to the size of the micrometeor particle. Because of the uncertainty of the theory it is permissible to make very crude assumptions in the present calculation. Essentially we wish to determine the energy necessary to fragment a cube of 10 μ linear dimension. From handbook data we find the strength of aluminum to be of the order of 10 kg per mm^2. Therefore, the force per $(10\ \mu)^2$ is 10^{-2} newtons. In order to produce a cleavage extending over a separation of the dimension of 1 atom, approximately 1 Å, we apply this force over a distance of 10^{-10} m. The energy required, therefore, is 10^{-12} j or 10^7 ev. At this rate we could break off 6×10^6 cubes of 10 μ dimension per m^2 surface area per sec. To remove a layer 10 μ thick would require 1600 sec.

It is seen that the erosion rate is extremely rapid, a 10 μ thickness being removed in about 1600 sec. The erosion rate is therefore 4×10^9 times as large as the one worked out in Model A and 2×10^7 as large as in Model B.

We shall now examine the reasonableness of Model C. The particle penetrates into the skin at a highly supersonic speed, the Mach number determined by the bulk sound velocity in the metal. The particle is therefore preceded by a shockwave of high strength. As the energy is passed on to the atoms of the metal skin within the shock cone, they participate in

the motion and reach very high temperatures.[3] This cone can probably be considered as made up of vaporized atoms.

As the kinetic energy is distributed among more and more atoms, their velocity reaches the sonic region. Here now we can no longer neglect the lattice structure of the skin material.

The energy is carried forward into the skin by compressional waves, in a manner depending very much on the elastic properties of the metal. The waves will be reflected from the discontinuity at the inside of the skin and from within the skin and will return again to the outer surface (see Fig. 1).

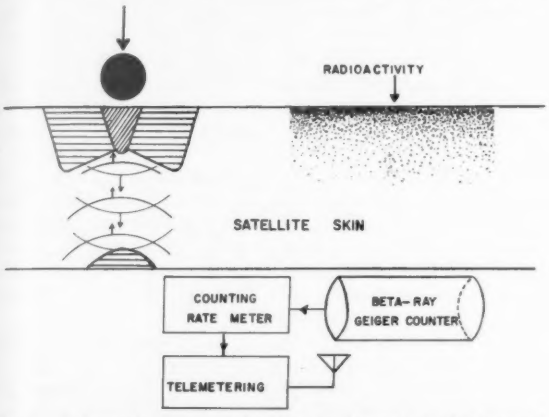

Fig. 1 Schematic diagram showing the impact of a high speed micrometeor and the resulting compression and tension wave; the cross-hatched portions indicate the parts of the skin which are removed by the impact either by vaporization in the cone or by spalling; the radioactive method for monitoring erosion in a satellite is shown on the right

At this point the treatment becomes rather uncertain and complex since now the breakup of the metal surface depends on the existence of faults, cleavage planes, and other features depending on the crystal structure, heat treatment, and—in general—the solid state properties of the metal.

We can now try to express this qualitative picture in mathematical form, and will derive an expression for the penetration depth of the micrometeor and for the fraction of its kinetic energy which is available for fragmentation of the metal.

Let a be the bulk velocity of sound in the skin material, v_0 the velocity, m_0 the mass, and S_0 the cross section of the incident dust particle; E_s is the sublimation energy per kg of the skin material. Applying conservation of energy considerations, at any instant we have

$$\tfrac{1}{2}m_0v_0^2 = m(E_s + \tfrac{1}{2}\dot{x}^2) \quad \ldots\ldots [1]$$

Now we consider m the mass in the shock cone to be volatilized

$$m \sim \rho x\left[S_0 + \frac{\pi}{3}\left(\frac{a}{v_0}x\right)^2\right] \quad \ldots\ldots [2]$$

Combining [1] and [2] and solving for $\dot{x}$, we find

$$\dot{x}^2 = -2E_s + m_0v_0^2\left[\rho S_0 x + \frac{\pi}{3}\rho\frac{a^2}{v_0^2}x^3\right]^{-1} \quad \ldots\ldots [3]$$

A solution of this set of equation gives $\dot{x}$, x, and m as functions of time. We cut off the solution when $\dot{x}$ reaches a, and define the penetration depth x_s and sublimated mass m_s.

In most cases we want to know just m_s and the elastic energy; then

$$\tfrac{1}{2}m_0v_0^2 = m_s(E_s + \tfrac{1}{2}a^2) \quad \ldots\ldots [1']$$

or

$$m_0M^2 = m_s\left(1 + \frac{2E_s}{a^2}\right)$$

where $M \equiv v_0/a$.

Typical values of a are $\sim 5 \times 10^3$ m/sec; typical E_s about 3 ev per atom (for Al). One kg of Al contains 6×10^{26}/2700 atoms; therefore $E_s = 4 \times 10^6$ j/kg. Using the values we find $2E_s/a^2 = \sim 0.3$.

We therefore derive $m_s/m_0 = 0.75\ M^2$; we also see that about one quarter of the incident energy goes to sublimate atoms, while the remainder appears as elastic energy.[4]

Our conclusion, therefore, is that the erosion rate is certainly much greater than Model A and Model B, but probably not quite as great as Model C. We must allow for the fact that a substantial fraction of the meteor energy is used in vaporizing the atoms in the shock cone, and that the breakup of the surface, which so efficiently erodes it, is a secondary effect.

Laboratory Experiments on Dust Erosion

We shall now discuss the possibility of checking the impact effects by means of laboratory experiments, i.e., by accelerating artificial dust particles to simulate meteor dust and observing the effects of their impacts on metal surfaces. Acceleration may be carried out by electrostatic means. The dust particles in the laboratory are first charged by allowing them to traverse a specially constructed discharge tube. The charge of the particle can be checked by a variety of means. Those particles which have picked up a sufficiently large charge are then accelerated further by an electric field in a type of linear accelerator. This design has the advantage of producing velocities in the meteor range without excessive accelerating voltages. Since the dust particles move rather slowly, it should be possible to apply a small voltage, of the order of 100,000 v, between the successive accelerating rings, switching this voltage as the particle goes along. In the experimental arrangement one can, therefore, vary the final velocity of the dust particle and within certain limits the size, mass, and nature of the particle as well. Of course, the target surface is completely under control so that various satellite skin materials can be tested in the laboratory. A second method under consideration in our laboratory is the acceleration of dust particles in a shock tube.

The results of these experiments will allow a better estimate of the erosion rate to be expected in the satellite experiment. Conversely, when one compares these laboratory erosion data with the actual erosion of the satellite skin measured above the atmosphere, it should be possible to obtain a more precise value of the incident flux of micrometeors.

Without waiting for the results of these laboratory experiments on dust particle impacts there is other evidence which can guide us in judging the effects of meteor impacts. The extensive experiments by Pugh (19) and colleagues and by Rinehart (20) show very clearly the effects of compression waves, tension waves, and their interactions. The energy released on the outside of the skin propagates as a compression wave, is reflected from the inside of the skin and could therefore lead to spalling of material, i.e., erosion on the inside of the skin (see Fig. 1).

[3] Of special interest from the point of view of the physics of solids is a study of the thermal spikes produced by these meteor impacts. A typical micrometeor imparts of the order of several times 10^{17} ev in each impact localized in a 10 μ region. This is a vastly greater energy than produced by α-particles emitted by radioactive nuclei or even heavy cosmic ray primary particles. It is interesting to compare the phenomena caused by meteor impacts with radiation damage. The latter, as brought out by Slater (11) and by Billington and Siegel (12) is the result of (a) displacement of atoms by particles passing through it, (b) particles which remain embedded as impurities, and (c) the ionization produced by the particles. The damage is caused by neutrons and heavy charged particles; radiations such as γ-rays and electrons produce very little damage (the ionization densities for typical α-particles, fast electrons, and γ-rays stand roughly in the ratio 600:1:0.02). A small volume of the metal around the track of the primary particle will be heated to a very high temperature (several 100,000 C) for extremely short periods (about 10^{-10} sec), resulting in sharp thermal pulses in the metal. Its effect on metals is somewhat similar to cold work. Slater (11) points out that the complete picture of radiation damage has not been worked out; e.g., effects of shock waves due to expansion by vaporization inside the metal have not yet been studied.

[4] This gives only the *initial* division of energy. A more detailed theoretical treatment should consider how much of the sublimation energy is recovered, how much of the elastic energy is (irreversibly) dissipated, etc.

The aim in the design of the skin, therefore, should be to reduce as much as possible the high stress concentrations. This speaks very strongly for a use of a meteor bumper of the type suggested by Whipple (7) and others.

A qualitative type of reasoning can be used to allow us to make a better decision on the type of skin material for a satellite or space station.

1 It is clear that the tensile strength of the material should be as high as possible.

2 The material should be free of sharp discontinuities, inhomogeneities, and other scattering centers which could cause local stress concentrations. Their existence might be established by sonic testing procedures.

3 Most important, the waves should be damped as rapidly as possible as they propagate through the skin material.

4 Also, in order to reduce the scabbing of material on the inside of the skin, an internal layer of material having very soft rubberlike properties might be advisable.

Measurement of Meteoric Dust Erosion on the Satellite Skin

The importance of *measuring* the erosion of the satellite skin due to meteoric dust impacts and sputtering is evident since the calculations give very uncertain results. There are three major points of importance:

1 Measurement of the skin erosion gives a measure of the integrated effects of meteoric dust impacts and of sputtering. The results serve to establish one of the most important environmental factors for satellites and for space flight in general.

2 They are of importance in connection with the design of further advanced satellites. The measurement would allow us, e.g., to gage the effects of erosion on different surfaces.

3 The change of the surface properties must be measured since they have far-reaching effects on the optical and aerodynamic properties of the satellites, and therefore subsidiary effects on the satellite albedo and temperature. These properties are important both for visibility and for the proper operation of the satellite instrumentation.

Radioactive Method

One of the most sensitive methods which can be used, and one which is at the same time most convenient for satellite applications, is the radioactive method proposed by the University of Maryland group for the Vanguard satellite. Radioactive material, preferably a β-ray emitter, is applied to the satellite skin. On the interior of the skin we monitor the activity with a β-ray detector (see Fig. 1). As dust impacts erode the skin, some of the radioactivity will be carried away and the detector output will decrease. Hence the erosion of the satellite skin is measured by observing the decrease in activity of a radioactive portion of the skin.

The outstanding advantage of the radioactive method is its extreme sensitivity. If the erosion rates are really as small as calculated in Model A, then it would be difficult to conceive of other methods of measuring the erosion in a finite time. A second advantage is the convenience with which the measurement can be carried out since it requires only the operation of a β-ray counter. Also the method is inherently accurate since it involves a digital counting operation (number of counts per second) rather than a delicate measurement of the surface property of the satellite.

The method has obvious advantages from the telemetering point of view. It is only necessary to monitor the detector occasionally. Data storage is unnecessary. Since the method is an integrating one, only a minimum amount of information needs to be transmitted. The scheme is, therefore, compatible with any telemetering system. The counting rate information could be multiplexed, for example, with temperature sondes or with other erosion sondes. The amount of power required is extremely small; we estimate about 10 v dc at 2 ma. The payload weight is of the order of 1 to 2 oz. There are no special requirements on the orbit and no special requirements on the orientation of the satellite. From all these points of view it is one of the simplest experiments to carry out in an initial satellite.

Design of Experiment

In order to design the satellite meteoric erosion instrumentation we must have some idea about the expected rate of erosion. As seen above, the limits are very wide. To make the method sensitive we must make sure that during the average lifetime of the satellite, about 10 days, a measurable fraction of the activity is eroded away.[5] Therefore it becomes necessary to design for different expected erosion rates, perhaps by making a number of such instrumentations and multiplexing them on one telemetering channel.

There are four considerations in the choice of the radioactive emitter:

1 It is advisable to pick a β-ray emitter of high energy in order to allow use of a rugged counter behind the skin. The α-particles will not be able to penetrate the skin (and may also damage it); a γ-emitter might adversely affect other instrumentation in the satellite; β-particles, however, have a limited range and would therefore only affect the counter which they are designed to operate.

2 The half-life should not be too short; otherwise the activity will decay away quite appreciably while the satellite is still in its orbit. The useful half-life should be at least several days.

3 The activity, which is inversely proportional to the half-life, should not be too weak. In other words, the half-life should not be too long; otherwise we require too much radioactive material in order to give an appreciable counting rate per second. Since the cosmic ray background acting on the counter might be expected to be of the order of 10 counts per sec, the β-activity should give a higher counting rate.

4 Finally, the radioactive nucleus chosen should be compatible with the skin material and should not lead to any undesirable chemical or metallurgical problems.

Choice of Emitter and Deposition Method

We can list a number of convenient β-active nuclei; the actual choice will depend on the result of tests of their reaction with the base metal of the satellite skin (see Table 2).

There appear to be at least six methods for incorporating the radioactive nuclei in the skin; they range from a thin

Table 2 Some β-emitters

Nuclide	Half-life, days	E_{ave}, mev
S^{35}	88	0.166
Ni^{59}	1.5	0.658
As^{73}	2.1	0.597
Ti^{61}	72	0.37
Zr^{89}	3.2	1.0
I^{131}	8	0.59
Os^{193}	45	0.35
Co^{56}	72	1.36
Rb^{86}	20	1.57
Y^{90}	2.5	2.6
W^{185}	77	0.46
Re^{186}	3.7	1.1
Au^{198}	2.7	0.82

[5] It is preferable, of course, to *measure* the erosion rate, but not necessary. Another point of view to adopt for this experiment is that a negative result (i.e., no appreciable decrease in radioactivity and therefore no appreciable erosion) demonstrates experimentally that meteoric erosion is of minor importance for the operation of satellites and space vehicles.

deposition on the skin to a uniform distribution of radioactive material throughout the skin. It is possible to paint on a thin coating but this would not really represent a true test of the metallic satellite skin. Another approach is evaporation in a vacuum, a method used for metallic coating of optical surfaces. A third approach is diffusion;[6] here radioactive atoms can penetrate through an appreciable skin thickness. It is possible also to prepare a radioactive skin and overlay it on the base metal by rolling methods. Finally, it is possible to activate a portion of the satellite skin directly in a nuclear pile where neutron bombardment produces radioactive atoms throughout the skin.[7] These methods, in the order given, will allow the radioactive material to penetrate different thicknesses of the satellite skin. The importance lies in the fact that the first methods are extremely sensitive to small erosion rates while the last method is rather insensitive. Considerations of this type lead us to the conclusion that the most useful method would be reactions between metal surfaces and radioactive ions in solutions: some variants are exchange reactions, self-diffusion and isotopic exchange, or electrodeposition. Classic experiments on the exchange between metal surfaces and radioactive ions in solutions were carried out first by von Hevesy in 1912 and have been pursued extensively by Haissinsky's school; the work has been reviewed by Simnad (14). By varying the time of exposure, it is possible to obtain layer thicknesses ranging from monatomic to many hundreds of atoms thick. Subsequent heat treatment establishes control over the penetration thickness.

After preparation of a "hot" skin it is possible to carry out laboratory tests by sandblasting the skin and measuring experimentally the decrease in activity. Such tests, and more elaborate ones, would, of course, form part of the design of the satellite experiment.

Scientific Results From Satellite Experiments

Special points of interest relate to the effects of *meteor streams* on the erosion rate. Since meteor streams occur very frequently throughout the year (see Table 3), it is possible to observe their effects rather directly. An important scientific question is whether the meteor streams, in addition to the larger meteors which produce the observable trails, also contain micrometeors which are most effective in producing erosion. The satellite experiments should be very helpful in settling this point by exhibiting an increase in the erosion rate during the period of the meteor stream.

Another question of interest concerns the *electrostatic interaction* between the dust particles and the satellite. The dust particles acquire an electric charge due to the photoelectric effect of the solar radiation in competition with electron pickup from the ionized interplanetary gas. These effects have been calculated and the conclusion reached that the dust particles can reach very high positive charges (15). Since the satellite will also arrive at an equilibrium charge, electrostatic effects between dust particles and the satellite are possible (16). It would be of great interest to determine such effects. One possibility lies in observing a day-night difference in the erosion rate. This difference could be presumably identified with the fact that the charge of the dust particle and the satellite is different on the night side of the earth due to the absence of solar radiation. Another effect to look for is a dependence of the erosion rate on the angle of inclination of the satellite orbit. If the dust particles are highly charged, they will be deflected by the geomagnetic field and will therefore reach their highest intensity in the vicinity of poles (15). An equatorial orbit could, therefore, show less dust erosion than a polar orbit. It may be possible to check this point in satellite flights beyond the Vanguard stage when the orbit inclination angle will be different from the presently contemplated value of 40 deg.

Table 3[1]

Name	Date of maximum	Mean hourly rate at max.[2]	Duration, days
Nocturnal			
Quadrantids	Jan. 3	100^r	2
Lyrids	April 21	10^v	2
Perseids	Aug. 12	50^v	12
Giacobinids	Oct. 10	1400^r	0.2[3]
Orionids	Oct. 19	15^v	10
Taurids	Nov. 3–10	10^v	27
Leonids	Nov. 16	10^v	5[4]
Geminids	Dec. 12	60^v	5
Ursids	Dec. 22	10^v	1
Daylight			
η-Aquarids	May 4	10^r	10
Piscids	May 7	30^r	9
Arietids	June 4	60^r	6
ξ-Perseids	June 6	40^r	15
54-Perseids	June 26	30^r	8
β-Taurids	July 3	40^r	10
α-Orionids	July 12	50^r	5
ν-Geminids	July 12	60^r	5
λ-Geminids	July 12	30^r	5
θ-Aurigids	July 25	20^r	11

[1] From Reference (6).
[2] r = from radar observations, v = from visual observations.
[3] Giacobinids show appreciable display only occasionally (about once in every 12 years).
[4] Leonids show occasional concentrated displays (periodicity 33 years?). Hourly rate given is the normal one.

A particularly interesting point of study is to establish whether there are any significant *variations* in the *concentration* of interplanetary dust during the solar cycle or even over a shorter time period. Observations of the zodiacal light and of the F-corona, the outer dust corona of the sun, have given us some ideas of the number of interplanetary dust particles between the sun and the earth; however, the number of observations are not sufficient as yet to establish any time variations. These might be associated with the emission of high speed ionized gas from the sun; if the dust particles are electrically charged as anticipated, the solar corpuscular stream should be able to "sweep out" a large number of dust particles from the interplanetary space around the sun extending even beyond the earth (18). One could perform a study of this effect by observing a possible variation in erosion rate of the satellite before and after a particularly large period of solar activity which results in the emission of a large quantity of ionized, high velocity gas from the sun.

If is seen, therefore, that erosion measurements of the satellite skin, aside from their utilitarian importance for space flight in giving us information about environmental conditions, are also capable of considerable scientific return in terms of a better understanding of the phenomena occurring near the earth and in interplanetary space.

Collision With Atmospheric and Interplanetary Gas

Although this paper deals primarily with meteoric dust erosion we will consider other erosive and corrosive effects which may be detrimental to the satellite skin. Collisions with *high velocity* gas atoms can lead to *sputtering* of the metal

(*Continued on page 1087*)

[6] Diffusion coatings can be of three types: solid-solid, solid-liquid, solid-gas. Under solid-solid we have, e.g., hot cladding; examples of solid-liquid diffusion are electroplating, hot dipping, plating from fused salts; under solid-gas we have, e.g., carburizing.

[7] A method in which the radioactive material is inside the skin has been suggested by M. J. Swetnick (13). Here the skin thickness would be measured by means of the number of back-scattered β-rays.

Experiments on Cone Drag in a Rarefied Air Flow

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Experiments were made to find the drag on the fore portion of a circular cone in a rarefied supersonic flow. Wind-tunnel tests on a cone of 15 deg half angle were conducted over a range of Reynolds number (based on free-stream properties and cone slant length) of 70 to 1500 at Mach 2 and 500 to 7000 at Mach 4. The experimental drag curves are in fair agreement with available boundary layer predictions if certain induced pressure and tranverse curvature effects are included, although some difference in trend of the experimental and theoretical curves is evident.

Introduction

THE experiments reported fall in what is usually termed the slip-flow regime. At the lowest air densities of the tests, the mean free path is on the order of 10–20 per cent of the average boundary layer displacement thickness. Such flow would usually be associated with high altitude flight (several hundred thousand feet up), although comparable ratios of mean free path to boundary layer thickness would be encountered in hypersonic flight at lower altitude.

The theoretical evaluation of drag in the slip-flow regime is still uncertain and incomplete. The present tests were designed to assist such evaluation by providing an experimental check of a simple flow. The experiments also provide, of course, a small amount of empirical data of direct applicability to flight problems.

Experimental Program

A simplified sketch of the model and balance is shown in Fig. 1. The model (A) consists of the fore portion of a conical surface having a total slant length of 3.7 in. Three models, having slant lengths of one half, one, and two inches, were used. The models were assembled with a gap of 0.005–0.010 in. between model and housing (B). The housing is supported by a streamlined strut (not shown). The space within the housing is connected by a passage through the strut to pressure measuring equipment.

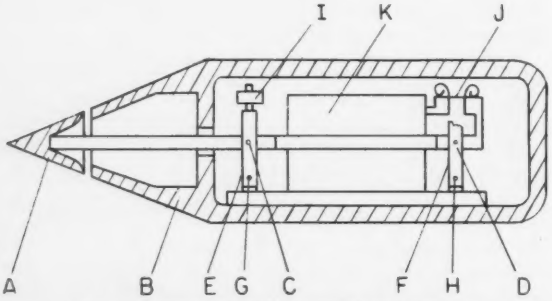

Fig. 1 Simplified sketch of model and balance

Received Aug. 20, 1956.

[1] Assistant Professor of Mechanical Engineering.

The model is supported by lateral torsion wires at C and D which connect to movable yokes E and F. The yokes are similarly supported at points G and H, where lateral wires attach (indirectly) to the housing. The restrain of axial motion introduced by torsional rigidity of the wires is essentially eliminated by adjustment of counterweights (e.g., I).

Axial force on the model is transmitted through a hair (J) to the armature of a variable reluctance pickup (K). The pickup (a product by the Wiancko Engineering Co. of Pasadena) was supplied with 3.2-kc, 20-v power and gave an output of about 0.12 mv per mg. The output was measured by a potentiometer circuit which has an accuracy of about 1 mg. Deflection of the pickup armature amounted to about 10^{-6} in. per mg. For the largest forces encountered (about 1700 mg), model deflection was consequently under 0.002 in.

All tests were performed in the No. 3 Wind Tunnel of the Low Pressures Project, University of California, Berkeley. Two nozzles giving Mach numbers of about 2 and 4 over a tunnel pressure range of approximately 50–150 microns Hg absolute were used with each model. Operating stagnation temperature (uncontrolled) was about 65–80 F.

Sensitivity of the pickup to temperature change required control of the housing temperature during test runs. Heating of the housing was accomplished by wrapping nichrome ribbon about its cylindrical portion. Pickup temperature was sensed by measuring its coil resistance with a bridge circuit. Its temperature was maintained at about 100 F by manual control of heater input. With such control the temperature could not be held closer than about one degree; however, by calibration it was possible to correct the force readings to a constant temperature.

Determination of total drag on the fore portion of the cone required measurement of pressure within the housing and force on the model, as determined from calibration of the pickup. Free stream properties were determined from measurement of stagnation conditions and nozzle discharge pressure (except that, for the Mach 2 nozzle, discharge Mach number from a nozzle calibration was used in preference to measured discharge pressure).

Results

The upper plot of Fig. 2 shows the measured drag coefficient. The left-hand curve is from the Mach 2 nozzle, the right-hand curve from the Mach 4 nozzle. Some of the scatter on this plot arises from the tunnel characteristics. Because of thinning of the nozzle boundary layer as flow rate increases, each nozzle exhibits a Mach number increase of about 10 per cent from the lowest to the highest flow rate. Therefore, points at the same Reynolds number for the different models are at slightly different Mach number.

The same data are shown in the upper plot of Fig. 3 with the inviscid drag (i.e., the pressure drag for frictionless flow) subtracted. The drag reported in this fashion can then be regarded as the drag due to viscous influences; it includes the shear drag and the increment of pressure drag caused by viscosity. Shown also on this plot are theoretical curves based on

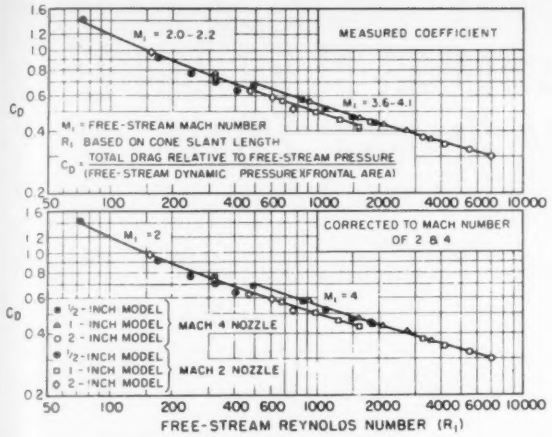
MEASURED COEFFICIENT
M_1 = 2.0-2.2
M_1 = 3.6-4.1
M_1 = FREE-STREAM MACH NUMBER
R_1 BASED ON CONE SLANT LENGTH
C_D = TOTAL DRAG RELATIVE TO FREE-STREAM PRESSURE (FREE-STREAM DYNAMIC PRESSURE X FRONTAL AREA)
CORRECTED TO MACH NUMBER OF 2 & 4
M_1 = 2
M_1 = 4
½-INCH MODEL
1-INCH MODEL
2-INCH MODEL
MACH 4 NOZZLE
MACH 2 NOZZLE
FREE-STREAM REYNOLDS NUMBER (R_1)

Fig. 2 Total drag coefficient (C_D)

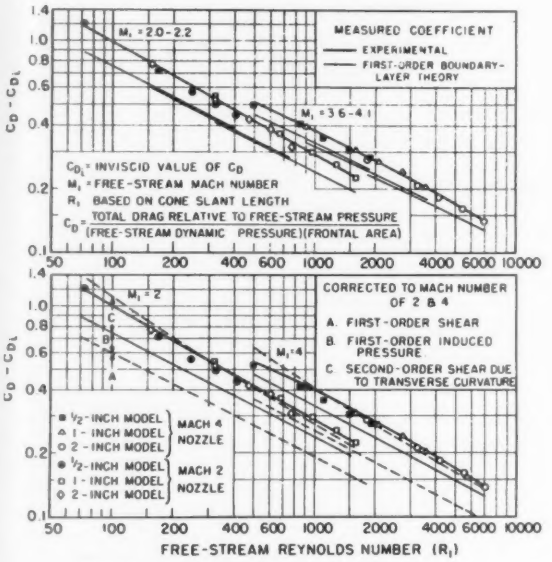
MEASURED COEFFICIENT
EXPERIMENTAL
FIRST-ORDER BOUNDARY-LAYER THEORY
M_1 = 2.0-2.2
M_1 = 3.6-4.1
C_{D_i} = INVISCID VALUE OF C_D
M_1 = FREE-STREAM MACH NUMBER
R_1 BASED ON CONE SLANT LENGTH
C_D = TOTAL DRAG RELATIVE TO FREE-STREAM PRESSURE (FREE-STREAM DYNAMIC PRESSURE)(FRONTAL AREA)
CORRECTED TO MACH NUMBER OF 2 & 4
A. FIRST-ORDER SHEAR
B. FIRST-ORDER INDUCED PRESSURE
C. SECOND-ORDER SHEAR DUE TO TRANSVERSE CURVATURE
M_1 = 2
M_1 = 4
½-INCH MODEL
1-INCH MODEL
2-INCH MODEL
MACH 4 NOZZLE
MACH 2 NOZZLE
FREE-STREAM REYNOLDS NUMBER (R_1)

Fig. 3 Viscous drag coefficient ($C_D - C_{Di}$)

first order[2] boundary layer analysis. They are the sum of a shear drag based on the adiabatic boundary layer of Young (3)[3] and a pressure drag derived from a local tangent cone approximation using the displacement thickness of Howarth (4). Only first order terms are retained.

The lower plots of Figs. 2 and 3 show the corresponding information corrected to Mach numbers of 2 and 4. The corrections were based on the theoretical first order drag, which was presumed to display an approximately correct Mach number dependence. The change in theoretical drag coefficient between the actual and nominal Mach numbers was simply added to the experimental drag coefficient.

The lower plot of Fig. 3 shows an additional theoretical curve (C). Curves A and B are the first order shear and pressure drags described. Curve C is an evaluation of the second order shear terms due to transverse curvature of the cone surface. The determination of this drag increment is based on the analysis of Probstein and Elliott (5).

In general, the scatter of the experimental data conforms with expected accuracy. An analysis of instrument error and calibration uncertainties indicated a possible error in drag coefficient of 2–3 per cent at Mach 4 and about 5 per cent at Mach 2. It is likely, however, that a systematic error arising from faulty operation of the pressure measuring equipment was present in the tests of the smallest cone, which adds somewhat to the uncertainty of the data at the lowest Reynolds numbers.

[2] By "order" is meant the power the inverse square root of Reynolds number in the theoretical expansion.

[3] Numbers in parentheses indicate References at end of paper.

Discussion

As evident from the curves, first order boundary layer theory underestimates the drag coefficient in the present regime of flow. At the lowest Reynolds number, first order shear drag is only 60 per cent of the total viscous effect. Addition of the pressure drag arising from interaction of the boundary layer and free stream still leaves the predicted viscous drag 25 per cent below the measured drag.

Most of the discrepancy between first order theory and experiment can apparently be explained by the influence of transverse curvature. The ratio of boundary layer displacement thickness to cone radius is fairly large, varying over the range of the tests from about 0.15 to 0.75, at the base of the model. As a result, the second order shear term arising from transverse curvature (the increment C in Fig. 3), is appreciable, particularly at low Reynolds number. Although other second order terms should, for the sake of completeness, also be included if the curvature influence is to be brought in, it is expected from available theoretical evidence that the influence of curvature on shear is the predominant second order effect in this flow regime.

An unexpected result is that slip does not appear to exert a strong influence. Comparing the experimental with the theoretical curves, one can imagine that the deviations at low Reynolds number may be slip inspired. The placement of the experimental curve, however, is still too uncertain to permit full confidence in the existence of these deviations. Failure of slip to show up clearly should probably not be surprising, since theory appears to make such a prediction. Present analysis indicates that slip has little, if any, second order influence. If true, a generous amount of slip appears necessary before its effect will be significant.

Conclusions[4]

1 The experiments show a greater drag than would be predicted by first order boundary layer analysis.

2 If a second order shear correction due to transverse curvature is included in the theoretical determination, fairly good agreement with experiment is achieved.

3 Deviations between the theoretical and experimental results at low Reynolds number suggest that some slip influence may be present. The deviations are not great enough, however, to be wholly convincing.

References

1 Ipsen, D. C., "Cone Drag in a Rarefied Gas Flow," University of California Engineering Project Report HE-150-114, Aug. 1953.

2 Ipsen, D. C., "New Experiments on Cone Drag in a Rarefied Gas Flow," University of California Engineering Project Report HE-150-128, April 1955.

3 Young, A. D., "Skin Friction in the Laminar Boundary in Compressible Flow," Report 20, College of Aeronautics, Cranfield, England, 1948.

4 Howarth, L., "Concerning the Effect of Compressiblity on Laminar Boundary Layers and Their Separation," *Proceedings Royal Society*, Series A, vol. 194, no. 1036, 1948, pp. 16–42.

5 Probstein, R. F., and Elliott, D., "The Transverse Curvature Effect in Compressible Axially Symmetrical Boundary-Layer Flow," Princeton University, Department of Aeronautical Engineering, Report 261, April 1954.

[4] More complete information on the experiments is available in (1, 2).

Some Aspects of the Measurement of Oscillatory Hydraulic Flow Including Nonlinear Effects[1]

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The venturi-type flowmeter is simulated by a model capable of analysis under nonsteady flow conditions. Nonlinear effects and the effect of inertia are included in the model chosen. The basic parameter in nonsteady flowmetering is shown to be a nondimensional frequency defined as the Strouhal number. The errors due to neglecting inertial forces in the flowmeter model have been calculated as a function of the Strouhal number. The analysis indicates that for a venturi type of meter the error in average flow rate calculated (neglecting inertia) is likely to be small for many practical cases. However, the phase lag and change in response, due to inertia, are likely to be important when an estimate of instantaneous flow is required.

Nomenclature

A = cross-sectional area
d = diameter of straight section of meter
f = friction factor
Δf = maximum deviation of friction factor from steady state value under oscillatory conditions
$f_1(\alpha,\ d_2/d_1)$ = function of half-angle α and diameter ratio d_2/d_1 of flowmeter
$FR(\omega)$ = frequency response of the flowmeter
$G_1(N_S)$ = special function of Strouhal number
$G_2(N_S)$ = special function of Strouhal number
IR = ratio of inertia in the convergent section of the flowmeter to the inertia in the straight throat section
J = inertia factor of flowmeter
$= (2L_t/u_{2,\ S.S.})K^2$
K = steady state flow coefficient of meter
$$= 1\Big/\sqrt{1-\left(\frac{A_2}{A_1}\right)^2+\frac{fL_f}{d}}$$
L = length
L_t = actual length of straight section or throat in flowmeter
N_S = Strouhal number (cf. Equation [20])
p = pressure
Δp = pressure drop across meter
$\overline{\Delta p_f}$ = steady state pressure drop due to friction in flowmeter
T = period of oscillation
t = time
u = flow velocity
x = distance in direction of flow
α = half-angle of conical convergence section of flowmeter (degrees)
μ = the dimensionless variation in flow velocity
$= (u_2 - u_{2,\ S.S.})/u_{2,\ S.S.}$
ν = frequency (cycles/unit time)
ρ = mass density of fluid
ϕ = phase angle between oscillating pressure drop across flowmeter and oscillating friction factor
ψ = dimensionless variation in Δp across flowmeter
$= (\Delta p - \overline{\Delta p})/\overline{\Delta p}$
ψ_o = maximum dimensionless variation in p across flowmeter during oscillatory flow
ω = frequency (radians/unit time)

Superscript

$(^-)$ = time average

Subscripts

1 = upstream from meter
2 = exit of contraction section of meter
3 = exit of constant-area section of meter
f = frictional equivalent
i = inertial equivalent
$S.S.$ = steady state

Introduction

THE problem of measuring nonsteady fluid flow has recently received considerable attention in the engineering literature (1, 2, 3, 4).[3] The general theory of nonsteady fluid flow applicable to nonsteady flow measurements has also been applied to the analysis of combustion stability in liquid propellant rocket motors (5, 6, 7). In the case of rocket combustion stability the important quantity to be determined is the frequency response of the propellant feed system. That is, the instantaneous pressure drop across the system is required under nonsteady flow conditions. In many industrial flowmetering applications the instantaneous mass flow is not as important a quantity as the average flow rate or the total mass flow. However, an analysis of the measurement of nonsteady flow gives information regarding both the average flow rate and the instantaneous flow rate. In this paper the venturi-type flowmeter is simulated by a simplified model which has all the characteristics which could lead to errors in nonsteady flowmetering. An analysis is presented which should allow flowmetering errors to be estimated.

Theory of Oscillatory Flow

Often under nonsteady flow conditions, the steady flow equations are used for calculating the instantaneous and the average flow rate. This procedure neglects the errors due to the nonsteady nature of the flow. In order that the errors involved in nonsteady flow measurement can be investigated analytically, a simplified model of a flowmeter is analyzed, taking into account not only the effect of the fluid inertia but also the fact that the energy-loss coefficients might vary from the steady state value under oscillatory flow conditions. The model chosen for analysis is shown in Fig. 1. The model consists of a convergent section in which inertia and friction ef-

Received Jan. 9, 1956.

[1] This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract No. DA-04-495-Ord 18, sponsored by the Department of the Army, Ordnance Corps.

[2] Research Group Supervisor; presently: Senior Scientist, Atomic Power Division, Westinghouse Electric Corp., Bettis Plant, Box 1468, Pittsburgh.

[3] Numbers in parentheses indicate References at end of paper.

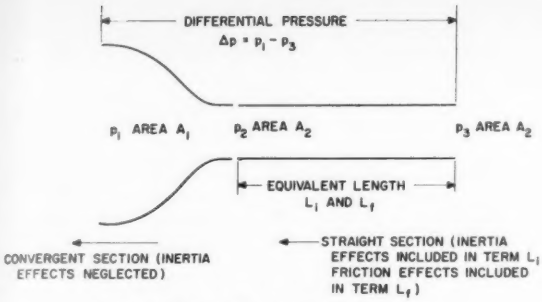
DIFFERENTIAL PRESSURE
Δp = p1 − p3
p1 AREA A1
p2 AREA A2
p3 AREA A2
EQUIVALENT LENGTH
Li AND Lf
CONVERGENT SECTION (INERTIA EFFECTS NEGLECTED)
STRAIGHT SECTION (INERTIA EFFECTS INCLUDED IN TERM Li FRICTION EFFECTS INCLUDED IN TERM Lf)

Fig. 1 Model of simplified flowmeter

fects are neglected. The flow in the convergent section is described by

$$p_1 - p_2 = \frac{\rho u_2^2}{2}\left[1 - \left(\frac{A_2}{A_1}\right)^2\right] \quad [1]$$

It is assumed that the fluid under consideration is incompressible. Downstream from the convergent section of the meter is constant-area section A_2. Two different lengths L_i and L_f are assigned to this straight section. L_i is the equivalent length required to describe the inertia of the meter, and L_f is the equivalent length required to describe the friction effects of the meter, including the losses in the contraction section. This model has two characteristics of most conventional flowmeters, inertia L_i and irreversible losses L_f. Because of its simple nature, the effect of these characteristics on oscillatory flow measurement can be investigated analytically.

Of the many types of flowmeters currently in use, the venturi meter is closest to the model chosen. The most important advantage of the venturi meter over orifice and flow nozzle meters is that the flow is well guided; consequently it might be expected that the venturi meter is most amenable to analysis.

In steady state conditions, the basic one-dimensional flow equations[4] are

$$p_{1,\,s.s.} - p_{2,\,s.s.} = \frac{\rho u^2_{2.s.s.}}{2}\left[1 - \left(\frac{A_2}{A_1}\right)^2\right] \quad [2]$$

and

$$p_{2,\,s.s.} - p_{3,\,s.s.} = \frac{\rho u^2_{2.s.s.}}{2}\frac{fL_f}{d} \quad [3]$$

The sum of these two equations is

$$p_{1,\,s.s.} - p_{3,\,s.s.} = \frac{\rho u^2_{2.s.s.}}{2}\left[1 - \left(\frac{A_2}{A_1}\right)^2 + \frac{dL_f}{d}\right] \quad [4]$$

The value of the flow velocity at the exit of the meter is then

$$u_{2,\,s.s.} = \frac{\sqrt{\frac{2}{\rho}(p_{1,\,s.s.} - p_{3,\,s.s.})}}{\left[1 - \left(\frac{A_2}{A_1}\right)^2 + \frac{fL_f}{d}\right]^{1/2}} \quad [5]$$

or in more conventional form

$$u_{2,\,s.s.} = K\sqrt{\frac{2}{\rho}\Delta p_{s.s.}} \quad [6]$$

where K is the flow coefficient of the meter, and $\Delta p_{s.s.}$ is the pressure drop across the meter.

In conventional practice, Equation [6] has been used to calculate flow rates under oscillatory conditions where the flow coefficient K is assumed to be constant. Various devices have been employed which give the average value of $\sqrt{\Delta p}$, and this average value is substituted in Equation [6] to give the average flow rate. In other words

$$\bar{u}_2 = K\sqrt{\frac{2}{\rho}}\,\overline{\sqrt{\Delta p}} \quad [7]$$

To facilitate analysis, assume that Δp fluctuates sinusoidally about a mean value $\overline{\Delta p}$; that is

$$\Delta p = \overline{\Delta p} + \overline{\Delta p}\psi_o \sin \omega t \quad [8]$$

where ψ_o is the maximum percentage variation in Δp. The value of $\overline{\sqrt{\Delta p}}$ can then be calculated (8) as

$$\overline{\sqrt{\Delta p}} = \sqrt{\overline{\Delta p}}\left(1 - \frac{\psi_o^2}{16} - \frac{15}{1024}\psi^4_o - \ldots\right) \quad [9]$$

If ψ_o is less than 0.5, the first two terms in the series are sufficient to describe the errors involved. Thus the average flow in terms of the mean pressure drop $\overline{\Delta p}$ is

$$\bar{u}_2 = K\sqrt{\frac{2}{\rho}}\sqrt{\overline{\Delta p}}\left(1 - \frac{\psi_o^2}{16}\right) \quad [10]$$

However, this equation can be rewritten as

$$\bar{u}_2 = u_{2.\,s.s.}\left(1 - \frac{\psi_o^2}{16}\right) \quad [11]$$

where

$$u_{2.\,s.s.} = K\sqrt{\frac{2}{\rho}}\sqrt{\overline{\Delta p}}$$

which is the steady state flow rate corresponding to a steady pressure drop equal to the mean value $\overline{\Delta p}$. In other words, Equation [11] expresses the error in using the flow rate $u_{2.\,s.s.}$ calculated from the mean pressure drop $\overline{\Delta p}$.

It should be noted that in deriving Equation [11] two important assumptions have been made. First, the inertia of the fluid in the meter was neglected; second, the flow coefficient K was assumed to be constant.

The effect due to the neglect of the fluid inertia is now investigated. The flow coefficient, however, is assumed to be constant and equal to the steady state value corresponding to the mean value $\overline{\Delta p}$. In Appendix A it is shown that the effect of a fluctuating friction factor on the analysis results is negligible if friction losses are small compared to the over-all pressure drop. In the analysis presented the effects of deviations from a steady state pressure drop corresponding to $\overline{\Delta p}$ are investigated.

Equation [6] is then rewritten as

$$\overline{\Delta p} = \frac{\rho u^2_{2.\,s.s.}}{2K^2} \quad [12]$$

and the nonsteady equation for the straight section of the meter is written (9) as

$$p_2 - p_3 = L_i\rho\frac{du_2}{dt} + \frac{\rho f L_f}{d2}u^2_2 \quad [13]$$

Equation [2] is rewritten as

$$p_1 - p_2 = \frac{\rho u^2_2}{2}\left[1 - \left(\frac{A_2}{A_1}\right)^2\right] \quad [14]$$

because of the assumption that the flow coefficient is constant for deviations from the steady state. Combining Equations [13] and [14]

$$\Delta p = p_1 - p_3 = L_i\rho\frac{du_2}{dt} + \frac{\rho u^2_2}{2K^2} \quad [15]$$

The quantities Δp and u_2 then refer to instantaneous values.

[4] The subscripts *S.S.* indicate steady state conditions.

Subtracting Equation [12] from [15]

$$\Delta p - \overline{\Delta p} = L_i \rho \frac{du_2}{dt} + \frac{\rho}{2K^2}(u^2_2 - u^2_{2,\ s.s.}) \ldots\ldots [16]$$

Substituting the nondimensional variables

$$\psi = \frac{\Delta p - \overline{\Delta p}}{\overline{\Delta p}} \qquad \mu = \frac{u_2 - u_{2,\ s.s.}}{u_{2,\ s.s.}}$$

the basic nonsteady-flow equation to be investigated is

$$\psi = J\frac{d\mu}{dt} + \mu^2 + 2\mu \ldots\ldots [17]$$

where $J = (2L_1/u_{2,\ s.s.})K^2$. This equation is nonlinear, but a series solution can be obtained using the reversion method of solution (10, 11, 12). The method of solution is outlined in Appendix B. The term ψ is obviously

$$\psi = \psi_o \sin \omega t \ldots\ldots [18]$$

from Equation [8]. The solution for μ (the fractional deviation of u_2 from $u_{2,\ s.s.}$) is (to the same order as Equation [11]) written

$$\mu = \frac{\psi_o \sin(\omega t + \Delta_1)}{2\left[1 + \left(\frac{J\omega}{2}\right)^2\right]^{1/2}} - \frac{\psi^2_o}{4J\omega\left[1 + \left(\frac{J\omega}{2}\right)^2\right]\left[4 + \left(\frac{2}{J\omega}\right)^2\right]} \times \left\{J\omega + \frac{\sqrt{1 + (J\omega)^2}}{J\omega}[\cos\Delta_2 - \cos(2\omega t + 2\Delta_1 + \Delta_2)]\right\} \ldots\ldots [19]$$

where $\Delta_1 = \tan^{-1} - (J\omega/2)$ and $\Delta_2 = \tan^{-1} - J\omega$. Three facts are at once apparent from Equation [19]. First, although the assumed nondimensional pressure drop is a simple sinusoidal variation, the nondimensional flow variation contains terms of multiple frequency. This fact is due to the nonlinear nature of the system. Second, the higher order terms do not have a time-average value of zero. Third, the nondimensional quantity $J\omega$ appears throughout the solution and consequently deserves consideration.

In terms of the physical quantities involved, $J\omega$ can be written as

$$J\omega = \frac{2L_i\omega K^2}{u_{2,\ s.s.}} = 4\pi\left(\frac{L_i}{u_{2,\ s.s.}}\right)\frac{K^2}{T}$$

where T is the period of oscillation in seconds. The quantity $L_i/u_{2,\ s.s.}$ is the length of time required for a particle of fluid to traverse the straight section of the meter. Consequently $J\omega$ is proportional to the length of time required for a particle of fluid to traverse the meter divided by the period of oscillation. The term $J\omega$ is simply the ratio of convective terms to acceleration term and is known as the Strouhal number. The significance of the Strouhal number has been presented in detail by Szebehely (13), and its applications to flowmetering are discussed in a recent literature survey (4, 10). For the purpose of the present report the Strouhal number is defined as

$$N_S = \frac{J\omega}{2} = \frac{L_i\omega K^2}{u_{2,\ s.s.}} \ldots\ldots [20]$$

The smaller the value of the Strouhal number, the closer the nonsteady equations are to the steady state equations.

The time-average value of μ can be found by taking the time average of both sides of Equation [19]. Thus

$$\bar{\mu} = -\frac{\psi^2_o}{4J\omega\left[1 + \left(\frac{J\omega}{2}\right)^2\right]\left[4 + \left(\frac{2}{J\omega}\right)^2\right]} \times \left[J\omega + \frac{\sqrt{1 + (J\omega)^2}}{J\omega}\cos\Delta_2\right] \ldots [21]$$

Eliminating $\cos\Delta_2$ by trigonometric identities, Equation [21] becomes

$$\bar{\mu} = \frac{-\psi^2_o}{16(1 + N^2_S)} \ldots\ldots [22]$$

The term $\bar{\mu}$ can be expressed as

$$\bar{\mu} = \frac{\bar{u}_2}{u_{2,\ s.s.}} - 1 \ldots\ldots [23]$$

and consequently in terms of $\sqrt{\overline{\Delta p}}$

$$\bar{u}_2 = \left[1 - \left(\frac{\psi^2_o}{16(1 + N^2_S)}\right)\right] K\sqrt{\frac{2}{\rho}}\sqrt{\overline{\Delta p}} \ldots [24]$$

and in terms of $\sqrt{\overline{\Delta p}}$

$$\bar{u}_2 = \frac{\left(1 - \frac{\psi^2_o}{16(1 + N^2_S)}\right)}{\left(1 - \frac{\psi^2_o}{16}\right)} K\sqrt{\frac{2}{\rho}}\overline{\sqrt{\Delta p}} \ldots [25]$$

For a given pressure oscillation magnitude the higher the value of N_S, the greater is the discrepancy between the use of only the first two terms in the series and the exact expression. Although the error appears to be leveling off with increasing N_S, it must be remembered that the solution presented contains only the first two terms of a series solution. These results are summarized in Table 1. If the oscillating pressure drop is not sinusoidal, it would be necessary to solve the nonlinear Equation [17] with the appropriate expression for ψ. Equation [17] could be solved for μ in any general case using an analog computer.

Theory of Instantaneous Flow Rate Measurement

Equation [19] is of considerable importance if the instantaneous flow rate is desired. Rewriting this equation in terms of the Strouhal number N_S

Table 1 Average flow rate in terms of $\overline{\sqrt{\Delta p}}$ and $\sqrt{\overline{\Delta p}}$

Conditions	In terms of $\overline{\sqrt{\Delta p}}$	In terms of $\sqrt{\overline{\Delta p}}$
Neglecting inertial effects	$\bar{u}_2 = K\sqrt{2/\rho}\,\overline{\sqrt{\Delta p}}$ ..... Eq. [7] *(independent of frequency and amplitude)*	$\bar{u}_2 = K\sqrt{2/\rho}\,\sqrt{\overline{\Delta p}}\,(1 - (\psi^2_o/16))$ .. Eq. [10] *(independent of frequency)*
Including inertial effects	$\bar{u}_2 = K\sqrt{\frac{2}{\rho}}\,\overline{\sqrt{\Delta p}}\left(\frac{1 - \frac{\psi^2_o}{16(1 + N^2_S)}}{1 - (\psi^2_o/16)}\right)$ Eq. [25] *(dependent on frequency and amplitude)*	$\bar{u}_2 = K\sqrt{\frac{2}{\rho}}\,\sqrt{\overline{\Delta p}}\left(1 - \frac{\psi^2_o}{16(1 + N^2_S)}\right)$ Eq. [24] *(dependent on frequency and amplitude)*

$$\mu = \frac{\psi_o}{2}\frac{\sin(\omega t + \Delta_1)}{\sqrt{1+N^2_S}} - \frac{\psi^2_o}{16(1+N^2_S)} \times \left[1 - \frac{\cos(2\omega t + 2\Delta_1 + \Delta_2)}{\sqrt{1+4N^2_S}}\right] \quad [26]$$

where $\Delta_1 = \tan^{-1} - N_S$ and $\Delta_2 = \tan^{-1} - 2N_S$. Using trigonometric identities, the second term can be written in terms of N_S, and thus

$$\mu = \frac{\psi_o}{2}\frac{\sin(\omega t + \Delta_1)}{(1+N^2_S)^{1/2}} - \frac{\psi^2_o[1 - G_1(N_S)\cos 2\omega t + G_2(N_S)\sin 2\omega t]}{16(1+N^2_S)} \quad [27]$$

where
$$G_1(N_S) = \frac{1 - 5N^2_S}{(1+N^2_S)(1+4N^2_S)} \quad [28]$$

$$G_2(N_S) = \frac{2N_S(N^2_S - 2)}{(1+N^2_S)(1+4N^2_S)} \quad [29]$$

The functions $G_1(N_S)$ and $G_2(N_S)$ are plotted in Fig. 2. It must be remembered that N_S is a function of the frequency ω.

The importance of the various terms in Equation [27] is easily understood in view of the fact that all terms but the first are directly proportional to ψ_o (a number less than one and greater than zero) squared. Even if ψ_o were as high as 0.5, the terms other than the first would amount to only about 5 per cent of the total flow fluctuation. Consequently, for the purpose of indicating the instantaneous mass flow, the first term in Equation [27] should be sufficient for most purposes. Equation [27] for the instantaneous mass flow then becomes

$$\mu = \frac{\psi_o}{2}\frac{\sin(\omega t + \Delta_1)}{(1+N^2_S)^{1/2}} \quad [30]$$

Since $\psi = \psi_o \sin \omega t$, it is at once apparent that the ratio of the mass flow fluctuation μ to the pressure drop fluctuation ψ can be expressed as a frequency response whose magnitude is

$$FR(\omega)_{mag} = \frac{1}{2(1+N^2_S)^{1/2}} \quad [31]$$

and whose phase angle is

$$\Delta_1 = \tan^{-1} - N_S \quad [32]$$

The frequency response of the flowmeter (i.e., magnitude and phase angle) is then a function of $J\omega/2 = N_S$ (cf. Figs. 3 and 4). After the amplitude of the pressure drop oscillation ψ_o has been ascertained, it is necessary only to multiply it by the magnitude of the frequency response for that frequency to obtain the magnitude of the flow fluctuation. The phase angle between the pressure drop fluctuation and the mass flow fluctuation is merely the phase angle of the frequency response. If the original differential equation (Equation [17]) is linearized, Equations [30–32] give the solution. It is then possible to estimate the instantaneous flow even when the pressure drop fluctuation is made up of several higher harmonics. As in the case in which the average flow is desired, the accuracy of such a linear treatment depends to a great extent on the distortion of the pressure drop oscillation from a sine wave and on the magnitude of the deviation of pressure drop from the mean value.

Application of Theory

As an example, consider the venturi flowmeter shown in Fig. 5. The equivalent length L_i describing inertia is the length of the throat or constant-area section down to the downstream pressure tap location plus an additional term which accounts for the inertial effects in the convergent section. The inertial effects of the convergent section can be put into a form equivalent to the terms $L_i(du_2/dt)$. Assum-

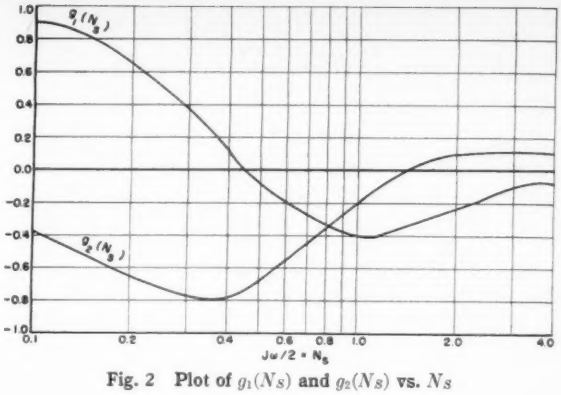

Fig. 2 Plot of $g_1(N_S)$ and $g_2(N_S)$ vs. N_S

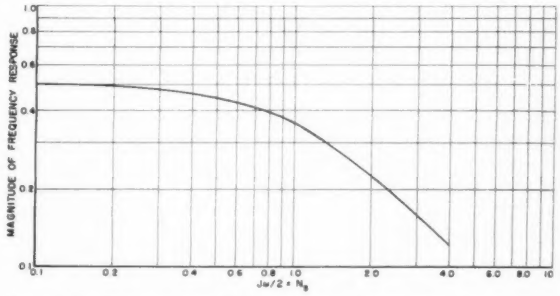

Fig. 3 Magnitude of frequency response of flowmeter vs. N_S or $J\omega/2$

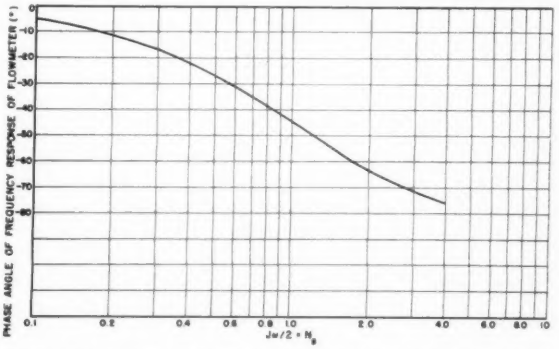

Fig. 4 Phase angle of frequency response of flowmeter vs. N_S or $J\omega/2$

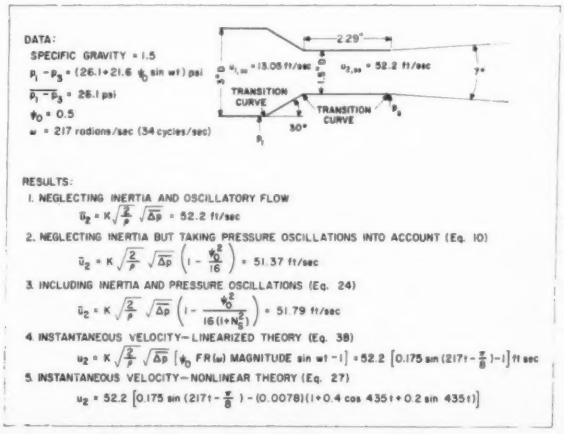
DATA:
SPECIFIC GRAVITY = 1.5
$p_1 - p_3 = (26.1 + 21.6\ \psi_o \sin \omega t)$ psi
$\overline{p_1 - p_3} = 26.1$ psi
$\psi_o = 0.5$
$\omega = 217$ radians/sec (34 cycles/sec)
2.29"
$u_{2,ss} = 52.2$ ft/sec
TRANSITION CURVE
TRANSITION CURVE
30°
RESULTS:
1. NEGLECTING INERTIA AND OSCILLATORY FLOW
$\bar{u}_2 = K\sqrt{\frac{2}{\rho}}\sqrt{\Delta\bar{p}} = 52.2$ ft/sec
2. NEGLECTING INERTIA BUT TAKING PRESSURE OSCILLATIONS INTO ACCOUNT (Eq. 10)
$\bar{u}_2 = K\sqrt{\frac{2}{\rho}}\sqrt{\Delta\bar{p}}\left(1 - \frac{\psi_o^2}{16}\right) = 51.37$ ft/sec
3. INCLUDING INERTIA AND PRESSURE OSCILLATIONS (Eq. 24)
$\bar{u}_2 = K\sqrt{\frac{2}{\rho}}\sqrt{\Delta\bar{p}}\left(1 - \frac{\psi_o^2}{16(1+N_S^2)}\right) = 51.79$ ft/sec
4. INSTANTANEOUS VELOCITY—LINEARIZED THEORY (Eq. 38)
$u_2 = K\sqrt{\frac{2}{\rho}}\sqrt{\Delta\bar{p}}\left[\psi_o\ FR(\omega)\ \text{MAGNITUDE}\ \sin\left(\omega t - \frac{\pi}{6}\right)\right] = 52.2\left[0.175 \sin\left(217t - \frac{\pi}{6}\right)\right]$ ft/sec
5. INSTANTANEOUS VELOCITY—NONLINEAR THEORY (Eq. 27)
$u_2 = 52.2\left[0.175 \sin\left(217t - \frac{\pi}{6}\right) - (0.0078)(1 + 0.4 \cos 435t + 0.2 \sin 435t)\right]$

Fig. 5 Illustrative example

ing one-dimensional flow in the convergent section, this term is

$$\frac{d}{dt}\int_1^2 u_{s.s.}\, dx$$

where $u_{s.s.}$ is now a function of position in the convergent section of the meter.[5] For a conical contraction section having a half-angle of α, the inertia term is

$$\frac{u_2 d_2^2}{2 \tan \alpha}\left[\frac{1}{d_2} - \frac{1}{d_1}\right] = u_2 d_2 f(\alpha, d_2/d_1) \quad [33]$$

It would be expected that the one-dimensional analysis of the convergent section would be most realistic for the smaller values of the half-angle α. The inertia term of Equation [33] for the convergent section can be compared with the inertia term for the throat section $L_t u_2$ in order to assess the relative importance of the inertia in the two portions of the meter. The ratio of inertia IR in the two sections is then

$$IR = \frac{f_1(\alpha, d_2/d_1)}{L_t/d_2} \quad [34]$$

The equivalent length L_i to be used in calculating N_S, Equation [20], is given by

$$L_i = L_t\left[\frac{1 + f_1(\alpha, d_2/d_1)}{L_t/d_2}\right] \quad [35]$$

The value of L_i given by [35] can be considered only as an estimate since the actual flow has been approximated by a one-dimensional flow under steady and oscillatory flow conditions. As shown in Appendix A, fluctuations in friction losses are a negligible factor in comparison with the inertia effects if the friction pressure drop is a small fraction of the total pressure drop across the meter.

The flow coefficient K defined in Equation [6] for the venturi meter in Fig. 5 is

$$K = \sqrt{\frac{1}{1 - (A_2/A_1)^2}} = \sqrt{\frac{16}{15}} \quad [36]$$

if the fluid is considered frictionless. The inertia ratio is 0.285. If the entrance half-angle were reduced, the inertia ratio would increase, consequently increasing the percentage of inertia in the convergent section. For the meter under study, according to Equation [35] the equivalent length (inches) for inertial effects L_i is $L_i = 2.29\,(1 + 0.285) = 2.94$.

The Strouhal number can be calculated from Equation [20]; that is

$$N_S = \frac{L_i 2\pi\nu K^2}{u_{2.\,s.s.}} = 0.0295\,\nu \quad [37]$$

where ν is in cycles per second. The Strouhal number is directly proportional to the size of the meter. Taking into account both inertia and pressure oscillations, the average flow rate can be found from [25] after the Strouhal number is known. Since the frequency is 34 cps (217 rad/sec), the Strouhal number is 1.0. The most accurate estimate of the average flow rate can be found from [25]; that is, $u_2 = 52.2 \cdot (1 - 0.0078) = 52.2 \cdot (0.9922) = 51.79$ fps. The results obtained for the average flow rate, based on the different equations which might be used, are summarized in Fig. 5. Using a mean value of the pressure drop gives a flow rate that is higher than the actual value, while using the mean value of $\sqrt{\Delta p}$ gives a flow rate lower than the actual value (taking into account both oscillatory pressure drop and inertia).

It is also possible to calculate the extent of the flow rate variations and the phasing of the flow rate and pressure drop oscillations. Since the pressure drop varies between 13.05 and 39.15 psi, Equation [6], which neglects inertia, would predict that the flow rate varies between 36.9 and 63.9 fps and is in phase with the pressure drop. In Fig. 6 the instantaneous nondimensional flow rate deviation from $u_{2.s.s.}$, calculated from [6], is plotted as a function of ωt. The nondimensional deviation of the pressure drop from the mean value plotted in Fig. 6 indicates that flow deviation is in phase with the pressure drop deviation if inertial effects are neglected.

[5] For orifice meters or other meters with sudden changes in cross-sectional area, the approach flow is not guided. Consequently this type of analysis has no validity for these meters.

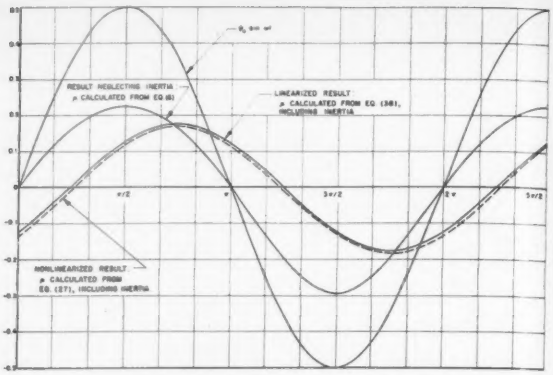
RESULT NEGLECTING INERTIA
p CALCULATED FROM EQ (6)
LINEARIZED RESULT
p CALCULATED FROM EQ (38), INCLUDING INERTIA
NONLINEARIZED RESULT
p CALCULATED FROM EQ. (27), INCLUDING INERTIA

Fig. 6 Comparison of methods for calculating nondimensional flow fluctuation from steady state

The linearized result for instantaneous nondimensional deviation of flow from $u_{2.\,s.s.}$ when inertia has been taken into account is given by Equation [30]. In terms of the frequency response $FR(\omega)$ of the meter [31, 32], the linearized result is

$$\mu = \psi_e FR(\omega) \sin \omega t \quad [38]$$

and for the present example

$$\mu = (0.5)(0.35) \sin (\omega t - 45°) \quad [39]$$

(Numerical values of the frequency response magnitude and phase angle were obtained from Figs. 3 and 4.) Equation [39] indicates that the flow rate varies between 43.1 and 61.34 fps and that the phase difference between the pressure drop and flow rate is 45 deg. Equation [39] is plotted against ωt in Fig. 6.

Equation [27] can be expected to give a more accurate estimate of the instantaneous flow rate than can Equation [30] because the nonlinearities have been taken into account. For the present example Equation [27] becomes

$$\mu = (0.5)(0.35) \sin (\omega t - 45°) - (0.0078)(1 + 0.4 \cos 2\,\omega t + 0.2 \sin 2\,\omega t) \quad [40]$$

Equation [40] is also plotted in Fig. 6. It is apparent that taking the nonlinear effects into account indicates a slight distortion of the resultant wave form indicated by the linearized analysis.

Conclusions

The use of a simplified model of a flowmeter makes it possible to obtain an analytical solution for the nonlinear flow measurement equations. The solution of this nonlinear equation shows that the nondimensional frequency defined as the Strouhal number is the parameter which most adequately describes the nonsteady nature of the oscillatory flow. The errors in neglecting the inertial effects, although taking into account the oscillatory pressure drop across a flowmeter, manifest themselves in two ways: (a) The actual average mass flow is greater than calculated, and (b) the flow rate is not in phase with the pressure drop. Both of these errors can be expressed in terms of the Strouhal number. On the basis of this study it is suggested that pulsating flow can best be measured using a flowmeter amenable to theoretical analysis. By use of the methods outlined, it is possible to estimate the magnitude and phase of the instantaneous mass flow rate and the average flow.

APPENDIX A

Effect of Fluctuating Irreversible Losses on Oscillatory Flow

The model of the flowmeter indicates that both the contraction coefficient K_c and the friction coefficient f would vary under oscillatory conditions. For the sake of discussion, K_c is assumed to remain constant, and f is assumed to vary sinusoidally about the steady state value and to be equal to $f + \Delta f \sin(\omega t + \phi)$, where ϕ is a phase angle between the pressure drop fluctuation and the resultant wall shear stresses in the straight section. Equation [13] becomes

$$p_2 - p_3 = L_i\rho \frac{du_2}{dt} + \frac{\rho f L_f}{2d} u^2_2 + \frac{\rho L_f}{2d} \Delta f \sin(\omega t + \phi) u^2_2 \ldots [41]$$

Equation [14] remains the same, and adding it to Equation [41] gives

$$\Delta p = p_1 - p_3 = L_i\rho \frac{du_2}{dt} + \frac{\rho u^2_2}{2K^2} + \frac{\rho L_f f u^2_2 \Delta f}{2d\, f} \sin(\omega t + \phi) . [42]$$

Subtracting Equation [12] from [42]

$$\Delta p = \overline{\Delta p} = L_i\rho \frac{du_2}{dt} + \frac{\rho}{2K^2}(u^2_2 - u^2_{2,\,s.s.}) + \frac{\rho L_f f}{2d} \frac{\Delta f}{f} u^2_2 \sin(\omega t + \phi) \ldots [43]$$

Substituting nondimensional variables

$$\psi = J \frac{d\mu}{dt} + \mu^2 + 2\mu + \frac{\Delta p_f}{\Delta p} \frac{\Delta f}{f} \sin(\omega t + \phi)\,[\mu^2 + 2\mu + 1] \ldots\ldots [44]$$

where $\Delta p_f = (\rho L_f f/2d) u^2_{2,\,s.s.}$, the steady flow friction drop in the meter. The additional term in Equation [44] is proportional to the product of the ratio of the friction pressure drop to the total pressure drop and the percentage deviation in the equivalent friction coefficient. In most flowmeters this effect might be expected to be small compared to the inertia effects likely to be encountered.

APPENDIX B

Solution of First Order, Nonlinear Flow Measurement Equation by the Reversion Method

The reversion method is outlined in detail in (10, 11, 12). The nomenclature employed by Pipes in (10) is used exclusively in this appendix. The basic equation is

$$a_1 y + a_2 y^2 = k\phi(t) \ldots\ldots [45]$$

in the Pipes nomenclature. The solution is

$$y = A_1 k + A_2 k^2 + \ldots \text{ (higher-order terms)} \ldots [46]$$

where

$$A_1 = \phi(t)/a_1 \ldots\ldots [47]$$

and

$$A_2 = \frac{-a_2 A^2_1}{a_1} \ldots\ldots [48]$$

The equation to be solved is

$$\psi_o \sin \omega t = J \frac{d\mu}{dt} + 2\mu + \mu^2 \ldots\ldots [49]$$

and in the Pipes nomenclature

$$y = \mu \qquad a_1 = J\frac{d}{dt} + 2 \qquad a_2 = 1$$

$$\phi(t) = \sin \omega t \qquad k = \psi_o \ldots\ldots [50]$$

Thus the flow deviation μ is in terms of a series in the pressure drop fluctuation ψ_o. Substituting in Equation [47]

$$A_1 = \frac{\sin \omega t}{J(d/dt) + 2}$$

or

$$J \frac{dA_1}{dt} + 2A_1 = \sin \omega t \ldots\ldots [51]$$

Equation [51] is a linear differential equation whose solution (neglecting the transient term) is

$$A_1 = \frac{1}{2} \frac{\sin(\omega t + \Delta_1)}{[1 + (J\omega/2)^2]^{1/2}} \ldots\ldots [52]$$

where

$$\Delta_1 = \tan^{-1} - \frac{J\omega}{2} \ldots\ldots [53]$$

Substituting in Equation [48],

$$A_2 = -\frac{1}{4} \frac{\sin^2(\omega t + \Delta_1)}{[1 + (J\omega/2)^2][J(d/dt) + 2]}$$

or

$$-J \frac{dA_2}{dt} - 2A_2 = \frac{\sin^2(\omega t + \Delta_1)}{4[1 + (J\omega/2)^2]} \ldots\ldots [54]$$

Equation [54] is a linear equation whose solution (neglecting the transient term) is

$$A_2 = \frac{1}{4J\omega[1 + (J\omega/2)^2][4 + (2/J\omega)^2]} \times \left\{ \frac{[1 + (J\omega)^2]^{1/2}}{J\omega} [\cos \Delta_2 - \cos(2\omega t + 2\Delta_1 + \Delta_2)] + J\omega \right\} . [55]$$

where

$$\Delta_2 = \tan^{-1} - J\omega \ldots\ldots [56]$$

References

1 Deschere, A. R., "Basic Difficulties in Pulsating-Flowmetering," *Trans. ASME*, vol. 74, 1952, pp. 919–924.

2 Hall, N. A., "Orifice and Flow Coefficients in Pulsating Flow," *Trans. ASME*, vol. 74, 1952, pp. 925–931.

3 Baird, R. C., and Bechtold, I. C., "The Dynamics of Pulsative Flow Through Sharp-Edged Restrictions (with Special Reference to Orifice-Metering)," *Trans. ASME*, vol .74, 1952, pp. 1381–1387.

4 Oppenheim, A. K., and Chilton, E. G., "Pulsating Flow Measurement, a Literature Survey," *Trans. ASME*, vol. 77, 1955, pp. 231–248.

5 Gunder, D. F., and Friant, D. R., "Stability of Flow in a Rocket Motor," *Journal of Applied Mechanics*, vol. 17, 1950, pp. 327–333.

6 Summerfield, M., "A Theory of Unstable Combustion in Liquid Propellant Rocket Systems," *Journal of the American Rocket Society*, vol. 21, 1951, pp. 108–114.

7 Crocco, L., "Aspects of Combustion Stability in Liquid Propellant Rocket Motors," *Journal of the American Rocket Society*, vol. 21, 1951, pp. 163–178.

8 Lindhal, E. J., "Pulsation and Its Effect on Flowmeters," *Trans. ASME*, vol. 68, 1946, pp. 883–894.

9 O'Brien, M. P., and Hickox, G. H., "Applied Fluid Mechanics," McGraw-Hill, New York, 1937.

10 Pipes, L. A., "The Reversion Method for Solving Nonlinear Differential Equations," *Journal of Applied Physics*, vol. 23, no. 2, 1952, pp. 202–207.

11 Cohn, G. I., and Saltzberg, B., "Solution of Nonlinear Differential Equations by the Reversion Method," *Journal of Applied Physics*, vol. 24 ,no. 2, 1953, pp. 180–186.

12 Cohn, G. I., and Saltzberg, B., "Solution of Nonlinear Differential Equations by the Reversion Method Through the First Thirteen Terms," *Journal of Applied Physics*, vol. 25, no. 2, 1954, pp. 252–254.

13 Szebehely, V. G., "Generalization of the Dimensionless Frequency Parameter in Unsteady Flows," David W. Taylor Model Basin, Washington, Report 833, Nov. 1952.

The Use of Solid Propellant Engines for Achievement of Super Velocities

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A review of the analytical relationships determining the velocity of a missile is presented. The effect of engine efficiency for low burned velocities and super velocities is discussed. The efficient staging for achieving velocities higher than can be achieved for a single stage is discussed. The large growth factors inherent when low performance engines are used for achievement of super velocities and the corresponding reduction of missile gross weight when higher performance rocket systems are used are illustrated. The basic case-bonded solid propellant rocket system and its characteristics which provide the high performance necessary for the achievement of super velocities are explained. New case materials and insulating materials are discussed which can be adapted to such a rocket system for improvement of engine weight efficiency.

Nomenclature

g	=	gravitational constant, 32.2 fps^2
I	=	total impulse, lb-sec
I_{sp}	=	propellant specific impulse, lb-sec/lb
M_1	=	initial mass of missile, slugs
M_2	=	mass of missile at burnout, slugs
W_e	=	weight of engine, lb
W_{mp}	=	weight of rocket engine metal parts, lb
W_L	=	weight of payload (total missile weight minus total rocket engine weight), lb
W_p	=	weight of propellant, lb
V_b	=	burned velocity, gravity-free and drag-free, ft/sec
I/W_e	=	impulse-to-weight ratio
M_1/M_2	=	missile mass ratio
W_p/W_e	=	propellant-to-engine weight ratio, engine weight efficiency

THE relatively recent interest in the attainment of high velocities has emphasized the improvements that can be gained by the reduction of inert component weight. Previously, most solid rocket engines were used for low velocity applications as jatos or boosters, where the weight of the load propelled was much greater than the weight of the rocket engine. The ratio of the weight of rocket engine inert parts to the weight of the load carried was very small, and reduction of the weight of rocket engine inert parts did not have a significant effect on weapon system performance. For these applications, however, improvement in propellant specific impulse values resulted in direct improvement in the weapon system. For this reason, solid propellant rocket engines were often evaluated on the basis of the one parameter propellant specific impulse. The most valid method of evaluation is to consider the complete weapon system and evaluate engines on the basis of weapon performance. This may result in many detailed studies which are quite time consuming; and, therefore, quicker methods of evaluation are desirable. When a high velocity is a primary objective of the missile system, the velocity at burnout is a valid parameter for engine comparisons, and its use will emphasize the importance of reduction of inert component weight for improvement of solid rocket engine missile systems.

The velocity at burnout of a single stage, solid rocket engine powered missile is given by the following equation for gravity- and drag-free conditions

$$V_b = gI_{sp} \log_e (M_1/M_2)$$

As discussed previously for applications where the missile mass ratio (M_1/M_2) is low, reduction in rocket engine inert weight will not reflect, in a like percentage, increase of burned velocity; and, therefore, improvements have been directed primarily toward improvement of propellant specific impulse. For applications where M_1/M_2 is high, a reduction of engine inert parts weight will result in a greater percentage increase in burned velocity. This equation indicates also that burned velocity increased linearly with propellant specific impulse regardless of the final velocity being considered. Continued improvement of propellant specific impulse will obviously result in higher burned velocity if the mass ratio of the waepon system is not affected. It should be noted, however, that for high velocity applications, improvement in propellant specific impulse may result in lower missile mass ratios (heavier metal parts because of high temperatures, pressures, etc.), and, therefore, result in a higher gross weight missile than might be attained with lower propellant specific impulse, higher efficiency engines.

For high velocity applications, it is apparent from the burned velocity equation that the missile mass ratio will increase with a reduction of rocket engine inert metal parts weight since the velocity equation can also be written (for drag- and gravity-free conditions)

$$V_b = gI_{sp} \log_e \frac{W_p + W_{mp} + W_L}{W_{mp} + W_L}$$

Rocket engines have been developed whose inert component weight is small with respect to the total engine weight, and which, therefore, provide the basic characteristics that will result in efficient high velocity missile applications. Such engines provide high total impulse values for low total engine weight—a performance parameter commonly referred to as impulse-to-weight ratio (I/W_e).

Although the term impulse-to-weight ratio is generally used in the propulsion field, its relationship to propellant specific impulse is not so universally understood. If the impulse-to-weight ratio is divided by propellant specific impulse, it can be shown that this resulting parameter is the ratio of propellant weight to total engine weight

$$\frac{I/W_e}{I_{sp}} = \frac{I}{I_{sp}W_e} = \frac{I_{sp} \times W_p}{I_{sp} \times W_e} = \frac{W_p}{W_e}$$

This relationship, the weight ratio of propellant to total engine weight, is referred to as the engine weight efficiency. It is readily apparent that the three parameters I/W_e, I_{sp}, and W_p/W_e are closely related, and specification of any two will automatically establish the value of the third parameter. This relationship is shown graphically in Fig. 1.

As previously stated, propellant specific impulse is the

Presented at the ARS Semi-Annual Meeting, Cleveland, Ohio, June 18–20, 1956.

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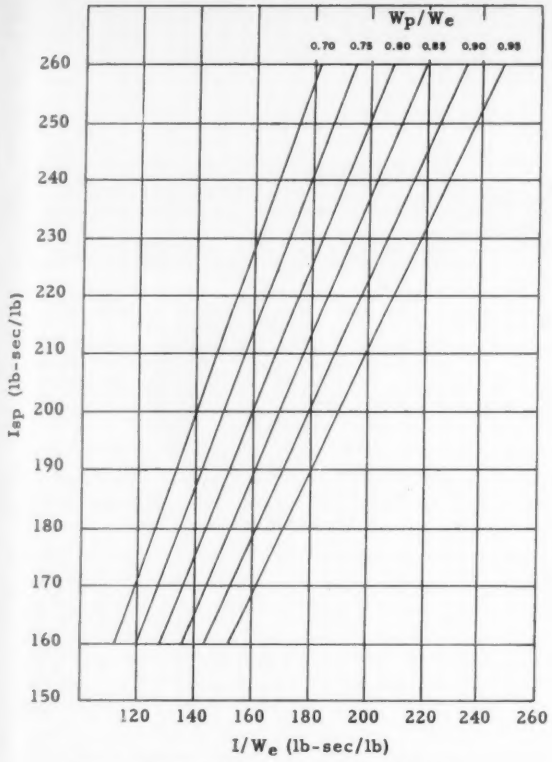

Fig. 1 Relationship of I_{sp}, I/W_e, and W_p/W_e

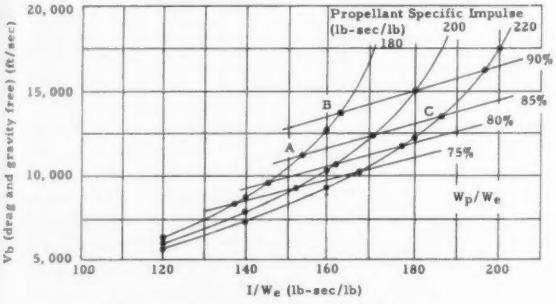

Fig. 2 "No-load" burned velocities

most significant parameter for low velocity applications which can be considered as approaching "full-load" applications. The high velocity applications tend toward the "no-load" condition. Consideration of this somewhat impractical application (unless the metal parts could be used for the destructive force) will emphasize the importance of low inert parts weight for high velocity applications. Burned velocity is plotted versus I/W_e in Fig. 2. This relationship indicates that if the I/W_e ratio for two engines is the same, the engine with the lower specific impulse propellant will accelerate to a higher velocity. It can also be seen that very high velocities can be achieved, regardless of the propellant specific impulse value, if the I/W_e ratio is high with respect to the propellant specific impulse value. These relationships are more easily understood when we note the ratio of propellant weight to total engine weight (W_p/W_e) cross-plotted in Fig. 2. This figure indicates that for constant values of W_p/W_e, burned velocity will increase linearly with propellant specific impulse. It also indicates that 5 per cent improvement in engine weight efficiency will result in a greater increase in burned velocity than an improvement in propellant specific impulse from 180 to 220 lb-sec/lb. This can be shown by reviewing points A, B, and C in Fig. 2. Assume that an engine exists whose characteristic locates it at point A. This engine has a weight efficiency of 85 per cent and a propellant specific impulse of 180 lb-sec/lb. Improvement in weight efficiency of 90 per cent (point B) will result in a greater improvement of burned velocity than would result in achieving a propellant specific impulse of 220 lb-sec/lb with the original weight efficiency of 85 per cent.

The effect of no-load conditions has been discussed but this condition, at least for most applications, is only of academic interest since some load must be propelled by the rocket engine. The load to be propelled by the rocket engine is referred to herein as a function of total engine weight. A ratio of total engine weight divided by load weight is used and is designated as W_e/W_L. The variation of burned velocity with engine to load weight ratio (W_e/W_L), propellant specific impulse (I_{sp}), and engine weight efficiency (W_p/W_e) is shown in Fig. 3.

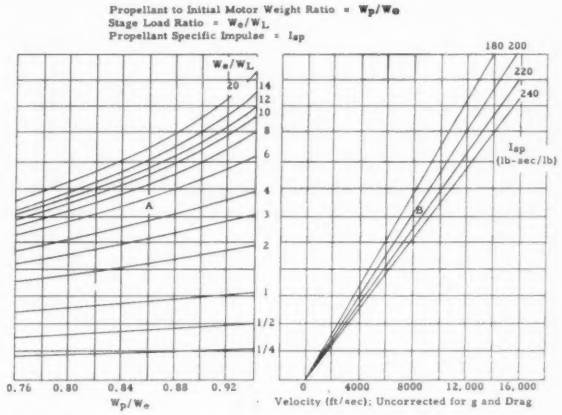
Propellant to Initial Motor Weight Ratio = Wp/We
Stage Load Ratio = We/WL
Propellant Specific Impulse = Isp
We/WL
Wp/We
Isp (lb-sec/lb)
Velocity (ft/sec); Uncorrected for g and Drag

Fig. 3 Velocity increment of stage (uncorrected for gravity and drag)

Fig. 3 fills in the area between the full-load and no-load conditions previously discussed. It should be noted that engine weight efficiency has a smaller effect on burned velocity at low values of engine-to-load weight ratios. The importance of high values of engine weight efficiency is shown when high velocities are required. As an example, assume that a burned velocity of 10,000 fps is desired and that the propellant specific impulse is 220 lb-sec/lb. If the engine weight efficiency is 94 per cent, the engine must weigh only four times the weight of the payload; however, if the engine weight efficiency is only 82 per cent, the engine must weigh twelve times that of the payload.

It should be noted that the above relationships may be used for determining the final velocity of a multiple stage missile (under drag-free and gravity-free conditions). Each stage must be considered individually and the velocity from each of the stage calculations can be added to obtain the weight of subsequently fired engines as well as the final payload.

Although it can be considered theoretically possible to use several stages of propulsion and to design practical missiles with high engine-to-load ratios for attainment of high velocities even with low weight efficiency engines, such a "brute force" approach results in tremendous missile growth factors. This can be demonstrated simply by comparing solid rocket engine propelled missiles designed to carry the same payload and to achieve the same velocity but which employ engines with different weight efficiencies for each of the missiles. The assumed motor performance parameters are tabulated for four weight efficiencies in Table 1.

For all four configurations, it is assumed that a 1500-lb payload (all weight exclusive of engine weights) is to be ac-

Table 1 Assumed motor performance parameters

Engine parameters	Engine designs A	B	C	D
I_{sp}, lb-sec/lb (for all stages)[1]	192	192	192	192
W_p/W_e, engine weight efficiency, %	75	80	85	90
I/W_e, impulse-to-weight ratio	144	154	163	173

[1] Since higher I_{sp} values would be attained at altitude, this assumption for all stages is conservative but is valid for comparison purposes.

Table 2 Weights of stage engines and total missile take-off weights

Parameter	Weight, lb, for engine designs per Table 1 A	B	C	D
3rd stage				
Metal parts	1,330	820	498	280
Propellant	3,990	3,280	2,825	2,520
Total engine	5,320	4,100	3,323	2,800
2nd stage				
Metal parts	6,050	3,050	1,600	800
Propellant	18,150	12,200	9,050	7,200
Total engine	24,200	15,250	10,650	8,000
1st stage				
Metal parts	27,500	11,400	5,140	2,285
Propellant	82,500	45,600	29,150	20,565
Total engine	110,000	57,000	34,290	22,850
Total				
Metal parts	34,880	15,270	7,238	3,365
Propellant	104,640	61,080	41,025	30,285
Total engine	139,520	76,350	48,263	33,650
Total Missile weight (including payload)	141,020	77,850	49,763	35,150

celerated to 15,000 fps final velocity (drag-free and gravity-free) achieved by the operation of three consecutive stages. Each stage is also assumed to produce $^1/_3$ of the total velocity or a stage incremental velocity of 5000 fps. The weights of the various stage engines as well as total missile take-off weights are tabulated in Table 2.

The percentage increase in burned velocity has been calculated for small increases in engine weight efficiency (W_p/W_e) for various values of engine-to-load ratio (W_e/W_L) and for various base values of engine weight efficiency from which the improvement is assumed to be made.

For the first set of calculations, referred to as Condition A, the propellant weight remained constant for the 1 per cent increase of the W_p/W_e ratio (from 80.0 to 80.8 per cent typical). The ratio of W_e/W_L was held constant for the incremental calculations, and since the total engine weight decreased for an increase of W_p/W_e, the total load also decreased. The results of these calculations are shown in Fig. 4.

The second set of calculations assumed that the total engine weight remained constant for a 0.01 increase of the W_p/W_e ratio (from 80.0 to 81.0 typical). The ratio of W_e/W_L was held constant for these incremental calculations, and since the engine weight was held constant, the load also remained constant. The results of these calculations are shown in Fig. 5.

The results shown for Condition A are those that could be expected from a weight reduction program with an established missile design. During such a program, it is practical to reduce the weight of the engine inert parts as well as the guidance and structure in order to retain the same engine-to-load ratio. It can be seen that for all values of engine-to-load ratio above approximately 3.0, the increase in burned velocity is greater than 1 per cent for an increase of 1 per cent in engine weight efficiency regardless of the initial engine weight efficiency (within the limits of the values shown). If the initial

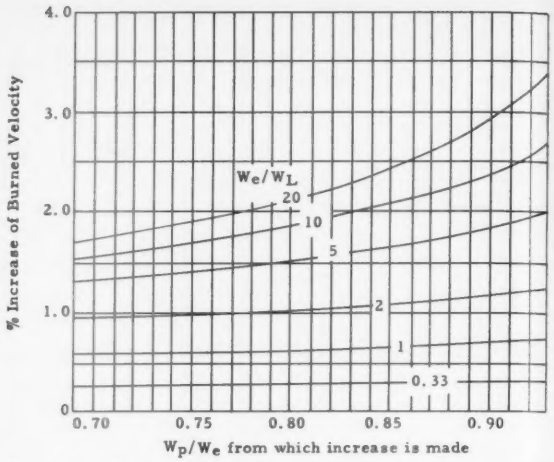

Fig. 4 Condition A—% increase of burned velocity for 1.0% increase of W_p/W_e by reduction of inert components only, and for a fixed W_e/W_L

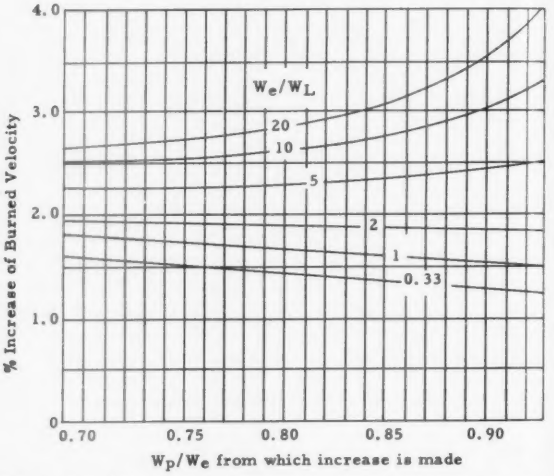

Fig. 5 Condition B—% increase of burned velocity for 0.01 increase of W_p/W_e by reduction of inert component weight and addition of propellant to maintain a fixed total engine weight, and engine to load ratio

engine weight efficiency is 78 per cent or higher, the percentage increase of V_b is greater than 1 per cent for engine-to-load ratios above 2.0.

The results shown for Condition B are those that can be realized from an increase in the state of art which permits an increase of 0.01 in the engine weight efficiency during the design stages so that additional propellant could be included to maintain a fixed total engine weight. Since additional propellant can be included for the savings achieved in inert parts weight, a 0.01 increase in the engine weight efficiency will result in greater than a 1 per cent increase in burned velocity. However, at low engine-to-load ratios, the percentage increase in burned velocity is much less than for higher values of engine-to-load ratios.

It should be noted that since burned velocity varies linearly with propellant specific impulse, the increase in burned velocity resulting from 1 per cent increase in propellant specific impulse is exactly 1 per cent. Therefore, the percentage increase shown for burned velocity is equivalent to the percentage increase of propellant specific impulse that is required to achieve the particular increase shown on the previous charts. It can, therefore, be concluded for high velocity applications that a greater increase in burned velocity can be achieved by 1 per cent increase (or 0.01 increase) in the engine weight

efficiency than by an equivalent increase in propellant specific impulse.

One of the most promising methods of reducing rocket engine inert component weight is the use of case-bonded solid propellant rocket systems. A sketch of a typical case-bonded rocket engine is shown in Fig. 6.

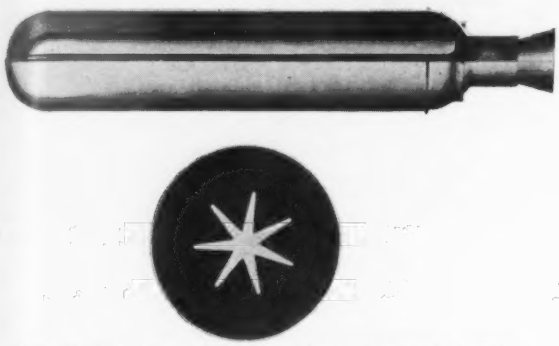

Fig. 6 Typical case-bonded solid propellant rocket engine

Because the propellant is bonded to the engine chamber and burning progresses from the interior toward the chamber wall, the chamber is protected from the heat of combustion by the propellant itself. Therefore, the "cold-strength" of chamber materials can be used for design purposes, and a thin lightweight engine chamber can be used. The case-bonded rocket engine system eliminates the propellant supports, obturation devices, and thick insulation often required in other types of solid propellant rocket engines. Elimination of these special inert components, as well as the use of a much lighter and thinner engine chamber, makes case-bonded solid propellant rocket systems readily adaptable to high performance systems because of the higher mass ratios that can be achieved. Case-bonded systems utilizing composite-type propellants have demonstrated outstanding qualities for such an application, since their elastic qualities allow the rocket engine to withstand extremely rough handling and large temperature changes, and to resist extremely high missile accelerations without structural failure of the propellant. Thiokol propellants are among those that have recently proved particularly desirable for use in case-bonded rocket engines.

In the case-bonded rocket system, the propellant is an integral part of the rocket engine. The propellant, metal components, missile attachments, and ignition system are designed as an integral unit. Design of the engine as an integral part of the weapon enables the lightest possible components to be designed in conformance with the over-all safety factors of the weapon system. In addition, the engine chamber usually forms part of the missile skin; therefore, it eliminates special structural supports or airframe members.

In addition to the "case-bonded" concept of engine design, application of new materials that have higher strength-to-weight ratios than the 4130 steel commonly used have indicated that additional weight reduction can be achieved. Two promising materials, XA-78 aluminum alloy and 6Al-4V titanium alloy, are among the outstanding examples of materials having higher strength-to-weight ratios which appear applicable for rocket engine cases. The strength-to-weight ratios for these materials, as well as for 4130 steel, are shown in Table 3.

It appears also that significant reduction in nozzle weight can be achieved by use of new materials, such as the titanium alloy previously mentioned. The use of high temperature insulation coatings which have good bonding and erosion characteristics, such as zirconium, on the inner surface of exit nozzle expansion cones permits lighter weight nozzles to be employed.

It appears that such inert weight reduction would permit the propellant-to-engine weight ratio to be increased to approximately 93 per cent. Improvements beyond this point, however, appear to be quite difficult to achieve. With the requirement for achieving high terminal velocities, such developments must be pursued to permit solid propellant rocket engines to provide the performance desired for these applications with the inherent high reliability demonstrated consistently throughout the past few years.

Table 3 Comparison of case materials

Material	Minimum yield strength, psi	Density, lb/cu in.	Strength-to-weight ratio, in.
4130 Steel	150,000	0.285	527,000
	170,000	0.285	596,000
	200,000	0.285	700,000
XA-78 Aluminum alloy	82,000[1]	0.100	820,000
6A1-4V Titanium alloy	140,000	0.16	875,000
	160,000	0.16	1,000,000

[1] Experimental results.

The improvements discussed herein have been approached from only the inert component viewpoint, and it has been shown that significant improvements can be achieved. It should not be inferred, however, that development effort should be directed along this one path only. Significant improvements can also be made by improving propellant specific impulse; however, it is apparent that higher specific impulse propellants will be suitable for high velocity applications only if their use permits high engine weight efficiencies to be realized.

Reference

1 Zucrow, M. J., "Principles of Jet Propulsion and Gas Turbines," John Wiley & Sons, New York, 4th Printing, Nov. 1952.

Effect of Meteoric Particles on a Satellite

(*Continued from page 1075*)

surface of the satellite. If we take the maximum velocity of gas in the upper atmosphere as equal to the escape velocity and add it to the velocity of the satellite, we reach a maximum relative impact velocity of about 18 kmps. For an N_2 molecule, about the heaviest molecule to be found at these high altitudes, this corresponds to an energy of about 40 ev. As remarked before, aluminum with a threshold of 125 v for sputtering would be completely immune to sputtering effects. Sputtering, however, may be of great importance if we consider space vehicles moving at velocities larger than satellite velocities. Such effects, therefore, must be considered for interplanetary vehicles moving at speeds in excess of 30 kmps.

Collisions with low velocity ions and with radicals present in the upper atmosphere and interplanetary space can lead to very undesirable corrosive effects. Because of their high reactivity they will enter into chemical combination with the metal surface of the satellite. These corrosive effects are distinct from those occurring in flames because of the much lower temperature. An experimental attack on this problem is essential and may be possible as a result of new techniques for producing and storing radicals at low temperatures (17).

Conclusion

We arrive at the following general conclusion: While it is not as yet possible to evaluate precisely all of the erosive effects which the satellite may encounter, the experimental approach for measuring skin erosion by radioactive means should give us a satisfactory over-all result for this important parameter of space flight.

(*Continued on page 1090*)

Cold-Forming Methods for Fabrication of Inert Rocket Components During Development

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A low cost, cold-forming process suitable for developmental operations is reviewed. The application of this technique to a precision ordnance rocket motor tube is described. The use of electric resistance welded low carbon steel tube as a raw material is indicated as satisfactory. The application of a cold-formed, pressure tight, high strength joint is discussed, and a means of obtaining cold-worked ultimate tensile strengths considerably in excess of 150,000 psi is described.

MOST metals have a greater capacity for elastic deformation after having once been stressed beyond their yield points. This plastic phenomena makes possible a number of unique methods and processes for producing specific shapes and unusual physical properties of material that could not be obtained any other way.

There are two important states of plasticity in metals: the thermoplastic range and the crystoplastic range. The thermoplastic range (known also as the "hot-work" range) occurs above the recrystallization temperature, where the crystal structure is not stable. The crystoplastic range, which is considered in this paper, is below the recrystallization temperature where the crystal structure is in a stable equilibrium; it is known as the cold-work range.

A low cost, cold-forming process suitable for developmental operations is reviewed; the application of a cold-formed, pressure tight, high strength joint is discussed; and a means of obtaining cold-worked ultimate tensile strengths considerably in excess of 150,000 psi is described.

The cold forming of metals is an art that has long been appreciated by designers and metals fabricators, and designers have used it to advantage in the production of many products. In addition to being an economical way of obtaining quantities of parts that would be difficult to make (or extremely expensive) by other techniques, the added "bonus" of close tolerances, high degree of smoothness in the surface finish, and increase in the yield strength and nominal ultimate strength usually results from the cold working of metals. Other important factors that are not always immediately recognized by those who are not metallurgists are the alignment of grain structure in the direction of working, and a degree of grain refinement.

The designer of inert components for rocket motors usually considers the permanent deformation under load as the criterion for failure. In some instances, excessive elastic deformation under load would be the criterion of failure, but it is only in rare instances that the designer permits large amounts of plastic deformation, with the rupture of the structure considered as the point of failure.

In view of these considerations, cold-worked materials would appear to be most desirable for rocket motors in designs that can use the high yield strength obtained by cold working. Low carbon steels can, in some instances, replace an annealed or normalized low alloy steel. This avoidance of costly strategic alloying elements, such as chromium, molybdenum, and nickel, provides a much happier picture for both the industrial mobilization planner and the cost-conscious production engineer.

While the rocket designer recognizes the advantages of cold-working, it is seldom that he is able to utilize cold forming during the developmental part of his program. Cold forming, which may be typified by deep drawing, is traditionally performed in large presses using expensive tooling, which in addition to being costly usually entails long lead times with little chance for design changes. The designer, working with limited finances and, probably more important, limited time, must prepare his developmental version using formed and welded plate, and machined components of alloy material. After the rocket has been developed on the basis of this design, and prior to the release of the unit for field evaluation or production, it must be "engineered for production." At this point, the eternal question of what is, and what is not, a functional design change arises. Bitter experience has shown that a "functional change" is often introduced, and considerable retesting (or retrogression into development activity) is necessary. The problems caused by this "retrogression," whether measured in dollars, the use of scarce engineering talent, or the delays in programs important to the national defense, are self-evident.

Many of the problems arising from the transfer of developmental techniques into production processes can be eliminated if the designer is able to use cold-formed parts in the developmental phase of the program.

At Aerojet-General, specialized portable machines have been procured and successfully employed for cold-forming rocket parts in conjunction with relatively lightweight, inexpensive tooling. This technique, known as the Aerojet-Barnhart Process, has given the rocket designer a tool which enables him to use cold-formed parts in all stages of development. This process is based on the application of well-known laws of metal forming, and the tooling procedures are adaptable for use with production-type machines without materially changing the end product.

The portable machines used to date are actually mounted on wheels and power is supplied by electric motors. Excellent dimensional reproducibility from part-to-part is achieved as a function of both tool design and positive start-and-stop positioning on the machine.

The ordnance rocket chamber shown in Fig. 1 is an example of the application of this process at Aerojet. Close coordina-

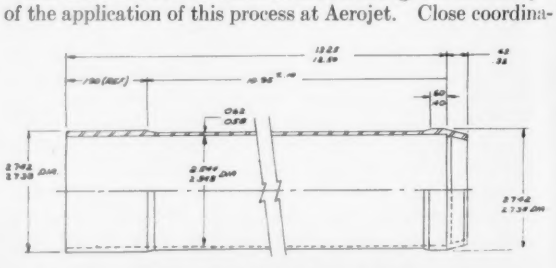

Fig. 1 Cold-formed motor tube

Presented at the ARS Semi-Annual Meeting, Cleveland, Ohio, June 18–20, 1956.

[1] Technical Specialist, Nuclear Project Dept.

tion between the rocket designer and metal fabricator permitted the rapid fabrication of cold-formed parts for use in the developmental phase of this rocket. The thickened end sections and the "drawn-in-place" nozzle plate seating shoulder are characteristic features of the design.

The service requirements of this part require that it be subjected to a static working stress of 100,000 psi without producing a permanent set. Normally, this design would dictate the use of AISI-A4130 tubing, heat treated to a minimum ultimate strength of 125,000 psi. In this particular instance, since it was the first attempt to apply the Aerojet-Barnhart Process, at Aerojet, parallel fabrication and evaluation programs were initiated for both machined and cold-formed parts. The cold-forming program was eminently successful. The formed pieces required only a minimum of machining, in the form of cut-off, threading, and slot milling; chip loss was at a bare minimum.

The motor tubes were formed from a noncritical, electric resistance welded, low carbon steel tubing. This is of extreme importance, since the domestic capacity for producing welded steel tubing is almost 100 times greater than that of seamless drawn tubing. The utilization of such an easily obtainable material for the mass production of ordnance rockets has long intrigued the designer and production engineer. The work accomplished to date has, for the first time, demonstrated statistically that this readily available nonalloy welded steel tubing can be employed in a precision ordnance weapon.

The U. S. Navy Bureau of Ordnance has sponsored procurement of cold-forming machines and the necessary supporting equipment to establish a pilot production facility at Aerojet-General in Azusa. The cold-forming techniques and "tooling tricks" developed with the lightweight, inexpensive tooling and portable machines are ready to be incorporated into the tooling for production presses without any functional change. The use of cold-formed parts in the early stages of development permitted a rapid determination of the feasibility of the weapon concept, while providing assurance that eventual production considerations were not being neglected.

As a result of the cold-forming work at Aerojet, a pressure tight, metal-to-metal joint has been devised which appears to have considerable applicability in rocket design. A cross section of this joint is shown in Fig. 2, which is a cutaway view of the cold-formed joint between a rocket motor tube and its nozzle plate. This particular photograph is of a tube and nozzle plate combination that has been static fired. It is evident from the photograph that there was no leakage of gas during the firing.

This joint was made cold; in fact, the propellant charge and the igniter were in place during the forming operation to duplicate the use of this type of assembly in rocket loading plants.

Joints of this design can eliminate the use of welding, threading, machining for a snap or lock ring, and other conventional methods of attaching chamber closures, whether these closures are at the end or in the midsection of a chamber. In the particular case illustrated, the use of such a joint also increases rocket performance by allowing a greater propellant loading density with free standing grains by eliminating the need for designing the grain to clear a minor thread diameter.

In work to this date, this cold-formed joint has been made using chrome-molybdenum steels as well as plain carbon steels. Individual joints were subjected to repeated hydrostatic pressure tests at design conditions without any evidence of joint leakage.

An additional example of the application of the cold-forming technique to inert rocket components is shown in Fig. 3. In the conventional design, the piece shown at B is machined from AISI-A4130 tubing with the end plate welded in place. The piece shown at A is cold formed from electric resistance welded, low carbon steel tubing, and employs the cold-formed joint in place of the welded end plate. Part A has adequate strength to satisfy the requirement of no yield at a working stress of 77,000 psi, and, in addition, weighs 16 per cent less than the part shown at B. A cross section of the cold-formed joint used in this application is shown in Fig. 4. The part can be, and usually is, designed to insure failure in the tubular part, rather than in the joint, as shown in Fig. 5. A joint of this type has been used to put a pressure tight bulkhead in the center portion of a tube, to join two tubular pieces to a common bulkhead, or, in many other ways, meet the specific requirements of the rocket designer.

A significant result of the development of cold-forming at Aerojet has been the cold-forming of nonalloy steel to

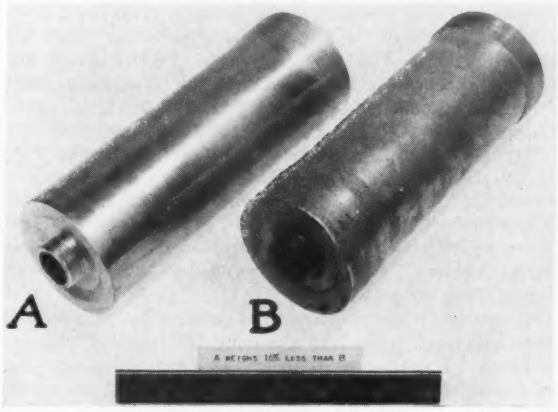

Fig. 3 Comparison of machined and welded part, with cold-formed part

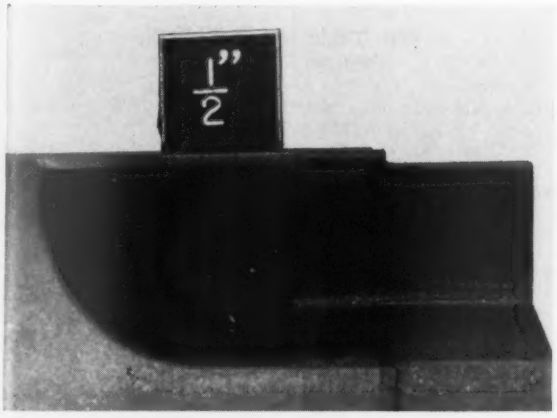

Fig. 2 Cold-formed pressure tight joint after static firing

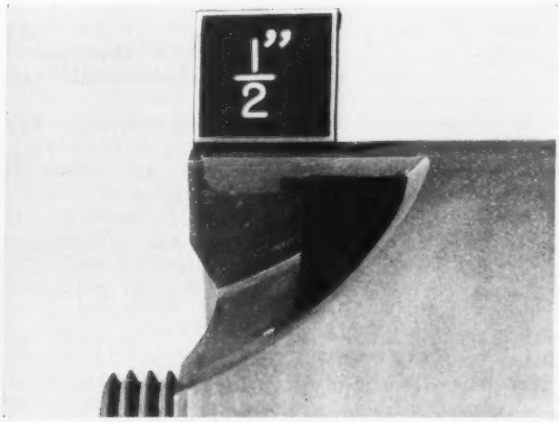

Fig. 4 Replacement of welded joint by cold-formed joint

Fig. 5 Results of hydroburst test

ultimate tensile strengths in excess of 150,000 psi. The fact that this has been achieved without resorting to the use of alloy materials heat treated after forming is considered a major forward step, since cold-worked strengths as high as this or higher have heretofore been achieved only in cold-drawn wire.

In the usual cold-drawing procedure, it is customary to pretreat the stock so that it is annealed or spheroidized; in either condition, the material will undergo strain hardening, following a rate of strain hardening curve from which the change in the yield point corresponding to a specific amount of cold working can be determined. The maximum yield strength and maximum degree of cold work that can be obtained are also determined from these curves.

Tentative curves of this type for some annealed plain carbon steels, with carbon contents up to 1 per cent, are presented in "Plastic Working in Presses," by E. V. Crane. These curves indicate that strengths in excess of 150,000 psi are not attainable with annealed plain carbon steel of any carbon content. Cold-forming results obtained at Aerojet substantiate the curves.

It was therefore necessary to re-examine the problem and determine some means of obtaining the required ultimate strength. It will be recalled that the strain hardening curve is determined with the aid of the true stress-strain curve. Therefore, it was postulated that the results of simple tensile tests should give a clue to what materials are capable of being worked to the desired ultimate tensile strength. Examination of the data available indicated that the noncritical materials most likely to give the required ultimate tensile strength would be plain carbon steels *quenched and tempered prior to cold working*. Preliminary tests have indicated that this premise was correct.

Motor tubes formed from AISI C1035 have shown strengths of 155,000 psi. At the present time, plans are being formulated for evaluating materials of various carbon contents and tempers to determine their strain hardening curves.

Data available for heat treated, low alloy steels indicate that even higher cold-worked ultimate tensile strengths (approaching 200,000 psi) can be achieved. These higher strengths will, in the main, be limited by tool-life considerations.

It is apparent that the low cost cold-forming process, and its corollaries, the cold-formed, pressure tight joint and cold-worked strengths in plain carbon steel in excess of 150,000 psi, are extremely valuable tools for the rapid development, and the transition to production, of rocket components.

Effect of Meteoric Particles on a Satellite

(*Continued from page 1087*)

References

1 Tobias, C. A., "Radiation Hazards in High Altitude Aviation," *Journal of Aviation Medicine*, vol. 23, 1952, p. 345.

2 Schaeffer, H. J., "Theory of the Protection of Man in the Region of the Primary Cosmic Radiation," *Journal of Aviation Medicine*, vol. 25, 1954, p. 338.

3 Shepherd, L. R., "The Possibility of Cosmic Ray Hazards in High Altitude and Space Flight," *Journal of the British Interplanetary Society*, vol. 12, 1953, p. 197.

4 Singer, S. F., "Cosmic Ray Effects at High Altitudes," *Journal of Aviation Medicine*, vol. 27, 1956, p. 111.

5 Grimminger, G., "Probability That a Meteor Will Hit or Penetrate a Body Situated in the Vicinity of the Earth," *Journal of Applied Physics*, vol. 19, 1948, p. 947.

6 Ovenden, M. W., "Meteor Hazards to Space Stations," *Journal of the British Interplanetary Society*, vol. 10, 1951, p. 275.

7 Whipple, F. L., "Meteoric Phenomena and Meteorites" in "Physics and Medicine of the Upper Atmosphere," Edited by C. S. White and O. O. Benson, University of New Mexico Press, Albuquerque, 1952.

8 Öpik, E. J., "Theory of the Formation of Meteor Craters," Pub. Obs. Astron. Univ. Tartu, vol. 28, 1936, p. 1.

9 Öpik, E. J., Private communication, April 1956.

10 Wehner, G. K., "Sputtering by Ion Bombardment" in "Advances in Electronics and Electron Physics," vol. VII, Academic Press, New York, 1955.

11 Slater, J. C., "The Effects of Radiation on Materials," *Journal of Applied Physics*, vol. 22, 1951, p. 237.

12 Billington, D. S., and Siegel, S., *Metal Progress*, vol. 58, 1950, p. 847.

13 Swetnick, M. J., Private communication, April 1956.

14 Simnad, M. T., "Radioisotopes in the Study of Metal Surface Reactions in Solutions" in "Properties of Metallic Surfaces," Institute of Metals, London, 1953.

15 Singer, S. F., "Measurements of Interplanetary Dust" in "Earth Satellites—Their Scientific Uses," University of Michigan Press, Ann Arbor, 1956. See also, "Geophysical Research with Artificial Earth Satellites," in "Advances in Geophysics," vol. III, edited by H. Landsberg, Academic Press, New York, 1956.

16 Bomke, H., (10th Anniversary Meeting of Upper Atmosphere Rocket Research Panel, Ann Arbor, Mich., Jan. 1956): Suggested the advisability of charging the satellite up to a very high potential by artificial means.

17 Broida, H., "Stabilization of Free Radicals at Low Temperatures," Conference on Unstable Chemical Species, N. Y. Academy of Science, March 1956.

18 Singer, S. F., "Studies of a Minimum Orbital Unmanned Satellite of the Earth (MOUSE) Part I. Geophysical and Astrophysical Applications." *Astronaut. Acta*, vol. 1, 1955, p. 171.

19 Pugh, E. M., v. Heine-Geldern, R., Foner, S., and Mutschler, E. C., "Kerr Cell Photography of High Speed Phenomena," *Journal of Applied Physics*, vol. 22, 1951, p. 487.

20 Rinehart, J. S., "Some Quantitative Data Bearing on the Scabbing of Metals under Explosive Attack," *Journal of Applied Physics*, vol. 22, 1951, p. 555.

Heat Transfer in a Rocket Nozzle

(*Continued from page 1097*)

4 Whaley, F. R., "The Exchange of Energy Between Polyatomic Molecules and a Metallic Surface," *Journal of Chemical Physics*, vol. 1, March 1933, p. 186.

5 Gomer, R., and Myer, L., "Energy Exchange Between Cold Gas Molecules and a Hot Graphite Surface," *Journal of Chemical Physics*, vol. 23, July 1955, p. 1370.[10]

6 Keenan, Joseph H., "Thermodynamics," John Wiley and Sons, New York, 1941, p. 31.

7 Sutton, George P., "Rocket Propulsion Elements," John Wiley and Sons, New York, 1949, pp. 51 and 64.

8 Jeans, Sir James, "An Introduction to the Kinetic Theory of Gases," Cambridge University Press, 1940, pp. 137–138.

9 Loeb, L., "Kinetic Theory of Gases," McGraw-Hill, New York, 1927, p. 96.

[10] An apparent α was computed from the data in this paper and additional data furnished by the authors in a private communication.

Heat Transfer Between Solid Particles and Gas in a Rocket Nozzle

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A method for calculating the degree of heat transfer between solid particles and gas in a rocket nozzle has been developed. It is assumed that the system is one in which the solid particles are no larger than the mean free path of the gas carrying them. It is further assumed that the particles are in directed velocity equilibrium with the gases. Under these conditions it is possible to calculate the heat transfer employing the kinetic theory of gases and a reasonable value of the thermal-accommodation coefficient. In order to deal with extreme conditions the method is illustrated with a carbon-hydrogen system containing eight parts of solid by weight, and the effect on specific impulse of the partial heat transfer is evaluated for a hypothetical rocket motor under specified conditions. The specific impulse in the case considered is diminished by less than 1 per cent.

Nomenclature[3]

A = cross-sectional area of rocket
A^* = cross-sectional area of nozzle throat
S = surface area of one solid particle
a = mass fraction of solid
b = mass fraction of gas
c_s = specific heat of solid
c_p = specific heat of gas at constant pressure
c_v = specific heat of gas at constant volume
c_p^* = specific heat of solid-gas system at constant pressure
c_v^* = specific heat of solid-gas system at constant volume
c_v' = translational heat capacity at constant volume per gas molecule
c_v'' = translational specific heat of gas at constant volume
g = acceleration due to gravity
H = enthalpy of solid-gas system
I_{sp} = specific impulse
L = mean free path
m = total mass of gas and solid
m_g = mass of gas
m_s = mass of solid
M = molecular weight of the gas
w = mass flow per second
N_{av} = Avogadro's number
N_s = number of molecular collisions per cm² per second
N = number of gas molecules per cm³
n = number of moles of gas
p = pressure
R = universal gas constant
r = solid particle radius
T_g = gas temperature
T_s = solid temperature
T_o = flame temperature
t = time
U = internal energy of solid-gas system in the absence of motion and gravity
V = volume
v = stream velocity
x = displacement
α = thermal-accommodation coefficient
η = specific heat ratio for the system from heat transfer considerations
ρ = density of solid-gas mixture
ρ_s = density of solid particle

Subscripts

i = initial state
f = final state
a = atmospheric conditions
e = exit conditions
t = throat conditions

1 Introduction

IN ROCKET propulsion systems employing a heterogeneous working fluid, the degree of heat transfer between the phases as the fluid goes through the nozzle could seriously affect the specific impulse. Maxwell, Dickinson, and Caldin (1)[4] investigated this heat transfer in an approximate fashion for a single particle but did not consider a system containing many particles nor did they evaluate the effect of partial heat transfer in terms of specific impulse. More recently, Altman and Carter (2) considered the special cases of thermal insulation and thermal equilibrium between the phases but did not attempt a solution of the partial heat transfer situation. It is the purpose of this paper to present a method for calculating the temperature difference between solid and gas exhaust components in a rocket nozzle associated with conductive heat transfer alone and to investigate the effect on specific impulse that such a temperature difference would have in a working fluid in which the weight per cent of solid is very high.

2 General Assumptions

The following general assumptions are made. Of these assumptions, 7 and 8 are to be noted particularly.

1 The solid phase is in the form of discrete spherical particles.

2 The working fluid is in steady flow, and the mixture of solid and gas is a uniform one.

3 The gas behaves as a perfect gas.

4 Only the gas molecules do work in expanding. This follows from the fact that if the solid particles are considered to be large molecules, their extremely high molecular weights make negligible the contribution of carbon to the pressure of the system.

5 The specific heats of the two phases are independent of temperature.

6 The solid particles and gas molecules are in axially directed velocity equilibrium throughout the nozzle.

7 Heat energy is transferred from the solid particle to the gas molecules only by random molecular collisions. See Appendix 5 for further discussion of this assumption.

8 The solid particles are no larger than the mean free path of the gas which carries them.

9 At the nozzle entrance the particles and gas are in

Received April 30, 1956.

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[3] Unless otherwise stated, the symbols listed here are used throughout. The cgs system of units is employed.

[4] Numbers in parentheses indicate References at end of paper.

thermal equilibrium at the flame temperature, and their temperatures are divergent beyond this point to an extent depending upon the heat transfer.

10 The solid-gas system is an adiabatic one, and the gas pressure decreases continuously along the nozzle axis.

11 Friction between the working fluid and walls is absent.

To illustrate the method, we consider a system of carbon particles of radius 10^{-6} cm (3) and hydrogen ($L \geqq 3 \times 10^{-6}$ cm) having a mass ratio of 8 parts carbon to 1 part hydrogen. The flame temperature is taken to be 2000 K and the chamber pressure 25 atm. This fluid is expanded to 1 atm in a rocket nozzle whose geometry is such that the fluid would have a pressure at the exit equal to the exterior pressure (1 atm) if the phases were in thermal equilibrium. The exit area ratio for this system is 4.59.

The problem in general is treated as follows. On the basis of the kinetic theory of gases the amount of heat transferred from solid to gas for selected area ratio intervals is computed. Then the resulting solid and gas temperatures are calculated for each interval from the computed heat transfer. From the rate of change of gas temperature with respect to solid temperature, a specific heat ratio η for the system is computed. Then exit velocity, pressure, and solid and gas temperatures are determined using this specific heat ratio, and from these exit conditions the specific impulse of the system is evaluated. The detailed steps as applied to the carbon-hydrogen system will now be presented.

3 Determination of Heat Flow and Resulting Exit Conditions

It is shown in Appendix 1 that when the mean free path of the hydrogen is equal to or greater than the particle radius, there is no appreciable temperature gradient outward from the first layer of gas molecules surrounding each particle. The heat flow from the solid per cm² of solid surface per degree K per second may then be written

$$\frac{Q}{(\text{cm}^2)(^\circ\text{K})(\text{sec})} = \alpha N_s c_v' \quad \ldots\ldots\ldots\ldots [1]$$

where N_s is the number of impacts per second of hydrogen molecules on one cm² of carbon-particle surface, and c_v' is the average heat capacity per hydrogen molecule. In the present calculation it is conservatively assumed[5] that only translational degrees of freedom are active, since the availability of the vibrational and rotational degrees is uncertain (4). The thermal-accommodation coefficient α expresses the ratio of the average energy transfer per collision to the energy transfer corresponding to the attainment of thermal equilibrium between solid and gas. For the present calculation we let $\alpha = 0.1$. This is somewhat below the values computed from the data of Gomer and Meyer (5) for the heat transfer between cold hydrogen and a smooth incandescent graphite filament at low pressures. Any errors, therefore, in the choice of values for c_v' and α are on the side of low heat transfer.

[5] This assumption applies only to the heat transfer.

[6] Area ratios: entrance, 123; exit, 4.59. Convergent cone angle, 85 deg; divergent cone angle, 30 deg.

From Equation [1] (see also Appendix 2) it follows that the incremental heat transfer from solid to gas in time dt is given by

$$dQ = \alpha c_v'' r^2 \left[\frac{8\pi M}{R}\right]^{1/2} \frac{p}{\sqrt{T_g}} (T_s - T_g) dt \quad \ldots\ldots [2]$$

If Equation [2] is substituted into the usual energy equation of steady flow (6), the resulting differential equation is too complex to be solved by practical means. However, on the basis of certain simplifying assumptions, Equation [2] may be solved approximately and evaluated in steps through the rocket nozzle from chamber to exit. The approximate solution of Equation [2] for a given interval is shown in Appendix 2 to be

$$\Delta Q = \frac{T_{gi} - T_{gf}'}{B} + \left[\frac{T_{si} - T_{gi}}{B} - \frac{T_{gi} - T_{gf}'}{kB^2\Delta t}\right][1 - e^{-kB\Delta t}] \quad \ldots\ldots [3]$$

where B is a constant, k is a constant times $p/\sqrt{T_g}$ (the bars denoting mean values for the interval), and Δt is the time required for a carbon particle to traverse the selected interval in which an amount of heat ΔQ is transferred from one solid particle to the surrounding gas molecules; T_{gf}' is the temperature that the gas would reach at the end of the interval if no heat is transferred to it from the solid.

Before proceeding with the approximate stepwise solution of Equation [3], it is necessary to plot the curves of velocity, gas temperature, and pressure—each as a function of area ratio for the case of complete heat transfer and of no heat transfer. The data for these plots (Figs. 1, 2, and 3) are obtained in a straightforward fashion from the usual equations of steady flow, which are derived in Appendix 4, and from the specific heat ratio expressions for complete and for no heat transfer given in Appendix 3.

The approximate method for obtaining T_g and T_s along the nozzle is outlined below, and the data are compiled in Table 1.

1 Starting with the inlet area ratio, select an appropriate final area ratio for the interval.

2 From the geometry of the given rocket configuration,[6] compute the final axial displacement corresponding to the selected final area ratio. For the first interval the initial position is taken as zero.

3 Assume that the velocity over the interval is that which would prevail under complete heat transfer conditions. Fig. 1 shows that at any given area ratio the velocities of the two extreme cases do not differ greatly. The velocity of the case in question must fall between the two limiting velocity curves. Thus as a reasonable approximation to local conditions affecting heat transfer, the velocity of the complete tranfer case at any point along the rocket axis will be used as the velocity of the case in question at that same point. Taking the initial velocity of the first interval as zero, the final velocity is evaluated from Fig. 1 at the final area ratio.

4 Now assuming constant acceleration over the given interval, compute the time interval Δt by

$$\Delta t = \frac{\text{distance}}{\text{average velocity}} = \frac{x_f^2 - x_i}{(v_i + v_f)/2} \quad \ldots\ldots [4]$$

Table 1 Heat transfer data for carbon-hydrogen system
$(m_s/m_g = 8)$

$(A/A^*)_i$	$(A/A^*)_f$	x_i, cm	x_f, cm	v_i, 10^4 cm/sec	v_f, 10^4 cm/sec	Δt, 10^{-6} sec	T_{si}, °K	T_{gi}, °K	T_{gf}', °K	$\bar{T}_g$, °K	$\bar{p}$, 10^6 dynes/cm²	ΔQ, 10^{-10} ergs	T_{sf}, °K	T_{gf}, °K
123	2.00	0.000	3.635	0.00	3.50	208	2000	2000	1967	1990	24.5	31.9	1983	1983
2.00	1.00	3.635	3.790	3.50	9.93	2.31	1983	1983	1747	1920	20.0	225	1866	1863
1.00	2.00	3.790	4.320	9.93	18.30	3.75	1866	1863	1217	1600	8.0	611	1549	1532
2.00	3.00	4.320	4.727	18.30	20.30	2.11	1549	1532	1321	1470	2.0	183	1454	1415
3.00	4.00	4.727	5.070	20.30	21.55	1.64	1454	1415	1272	1400	1.25	127	1388	1337
4.00	4.59	5.070	5.249	21.55	22.10	0.820	1388	1337	1271	1300	0.80	56	1359	1300

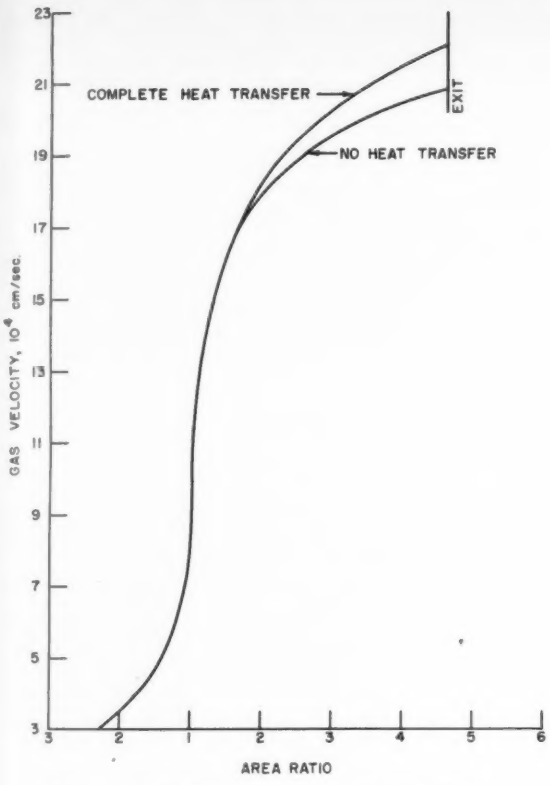

Fig. 1 Gas velocity vs. area ratio—extreme cases

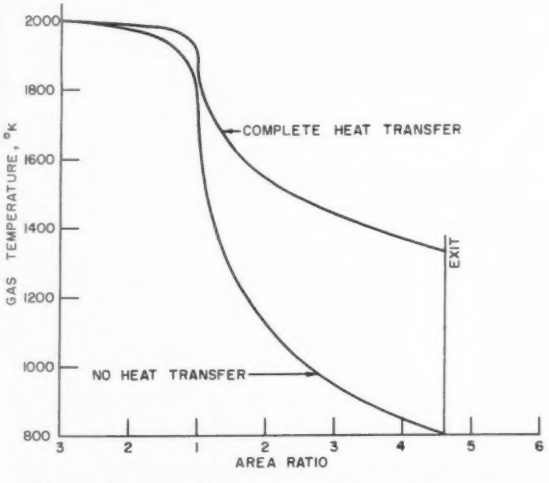

Fig. 2 Gas temperature vs. area ratio—extreme cases

5 Compute the final temperature for the interval that the gas would reach, assuming no heat transfer. This is done by writing the energy equation of steady flow in the form

$$T_{gf}' = T_{gi} - \frac{v_f^2 - v_i^2}{2bc_p}$$

where T_{gi} and v_i are known initial conditions and v_f has been evaluated in step 3.

6 Approximate the average temperature over the interval. This is done by extrapolating the computed gas temperature curve from the previous interval and evaluating its mean point for the present interval.

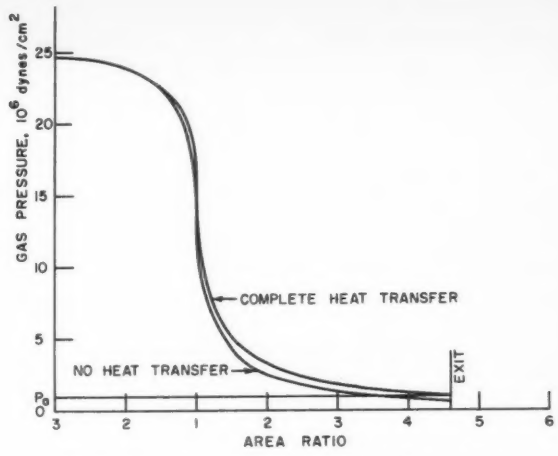

Fig. 3 Gas pressure vs. area ratio—extreme cases

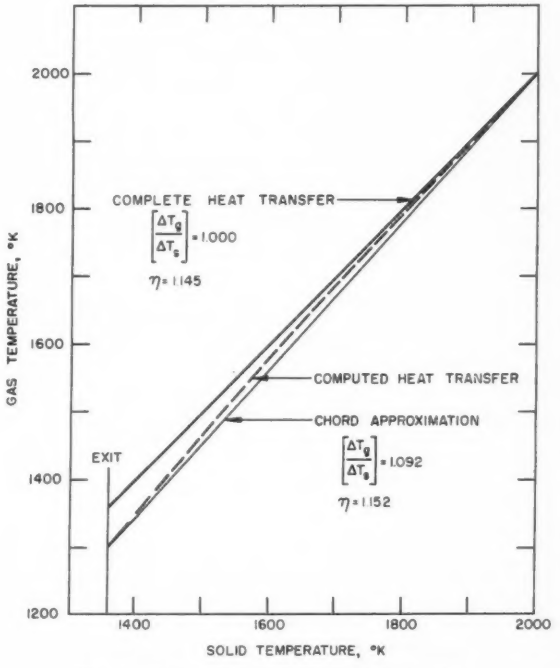

Fig. 4 Gas temperature vs. solid temperature

7 Approximate the average pressure for the interval as in step 6.

8 Solve for ΔQ employing Equation [3].

9 Calculate the final temperatures of both solid and gas for the interval from Equations [2-5] and [2-8]. In these equations Q becomes ΔQ when $T_s = T_{sf}$ and $T_g = T_{gf}$.

10 For the second area ratio interval, take initial conditions from the final conditions of the first interval, and compute the remaining unknowns just as before. Repeat the procedure until the length of the nozzle is covered.

Fig. 4 shows a plot of the gas temperature as a function of the solid temperature from the data of Table 1. Since this curve is nearly linear, a single chord approximation to the slope of the curve between the nozzle entrance and exit is drawn, and the slope $\Delta T_g/\Delta T_s$ is evaluated. For a given slope, there corresponds a specific heat ratio η for the system (see Appendix 3). The value of η, computed for the resulting amount of heat transfer, is shown in Fig. 4. With this value of η, exit conditions are computed from the equations of Appendix 4 and listed in Table 2.

Table 2 Exit conditions and specific impulses for complete, partial, and no heat transfer

	v_e, 10^4 cm/sec	T_{g_e}, °K	p_e, dynes/cm²	I_{sp}, sec	I_{sp} Loss, sec	I_{sp} Loss, per cent
Complete transfer	22.10	1331	1.013	226	...	...
Computed transfer	22.04	1303	1.003	225	1.0	0.4
No transfer	20.80	805	0.60	200	26	12

4 Calculation of Specific Impulse

Having computed exit conditions, it is now possible for one to evaluate the specific impulse of the system in question. The specific impulse I_{sp}, including exit-pressure correction, is computed from exit conditions by

$$I_{sp} = \frac{v_e}{g} - \left[\frac{bR}{Mg}\frac{p_a - p_e}{p_e}\frac{T_{g_e}}{v_e}\right] \quad [5]$$

where a refers to atmospheric and e to exit conditions. Equation [5] is valid provided that the rocket flows full at the exit, which occurs if $p_e \geqq 0.4p_a$ (7). The exit pressure shown in Table 2 satisfies this condition. Impulse values for the case of complete heat transfer, computed transfer, and no transfer are shown in Table 2. These results indicate that while the system could lose as much as 12 per cent of its theoretical impulse if no heat energy were transferred from solid to gas, less than 1 per cent is lost from the expected amount of heat transfer.

A similar calculation was carried out with a carbon-hydrogen working fluid in which carbon particles ten times the size of those previously assumed were used in the calculation, i.e., 10^{-5} cm in radius instead of 10^{-6} cm. Under comparable conditions of flame temperature, pressure ratio, and m_s/m_g, the loss of impulse was only 2 per cent. Here the particle size is somewhat larger than the mean free path of hydrogen at the inlet. The error involved in assuming that the temperature of the hydrogen molecules striking the particle equals the bulk temperature is discussed in Appendix 1.

One might ask how it is possible for the loss in specific impulse to be only 12 per cent with nearly 90 per cent of the working fluid being ejected from the nozzle at the flame temperature. Two factors seem to be involved here. One is that although the solid is in great excess, its gross heat uptake per degree of temperature rise is not several times that of hydrogen but is just about equal to it [$c_s = 2.05 \times 10^7$ erg/(g)(°K), $c_p = 1.65 \times 10^8$ erg/(g)(°K)]. The other factor is that when there is no heat transfer, the hydrogen overexpands (on the assumption that the nozzle flows full) and is ejected at a temperature lower (and hence higher velocity) than that at the exit for complete heat transfer (Figs. 2 and 3). The ratio of v_e', the fluid velocity at the exit for no heat transfer, to v_e, that for complete transfer, is from the energy equation of steady flow

$$\frac{v_e'}{v_e} = \sqrt{\left(\frac{bc_p}{ac_s + bc_p}\right)\left(\frac{T_o - T_{g_e}'}{T_o - T_{g_e}}\right)} \quad [6]$$

The first factor under the radical tends to reduce this ratio, while the second factor tends to raise it.

5 General Remarks on the Method

The method of computing the amount of heat transfer is, of course, a first order approximation, but since the impulse loss in the case presented is small, a first order approximation is adequate. The method may be made more exact by the use of many small intervals for the calculations. Also, the method may be applied repeatedly as follows. After making the first order calculation outlined in Section 3, one repeats the same process using the values of velocity and average temperature and pressure from the first order calculation. This may be extended in an iterative fashion until the desired accuracy is achieved.

In reference to Fig. 4, cases may arise where T_g vs. T_s is not sufficiently linear to permit the evaluation of $\Delta T_g/\Delta T_s$ by one chord from the nozzle entrance to the exit. Such cases may be treated by using a number of chord approximations to the curve and evaluating η for each chord. Using these values of η for their associated area ratio intervals, one may obtain exit conditions by stepwise calculations. The necessary relations are obtained by combining Equations [4-1], [4-2], and [4-4] and evaluating them at initial and final points for a given interval.

APPENDIX 1

Justification of Equation [1]

Consider a hot solid particle surrounded by cooler gas molecules. Those molecules, type I, which will next collide with the solid particle had their last collision with molecules (defined as type II) at a distance of one hydrogen mean free path from the solid particle.[7] Type I molecules will be at the body temperature of the gas unless an appreciable portion of type II molecules had their last collision with the solid particle. That fraction of type II molecules which are hot is given approximately by the ratio of the solid angle subtended by the particle at a point one free path away to the solid angle subtended by all space from that same point. This ratio is approximately

$$\left[\frac{\text{no. of hot molecules}}{\text{total no. of molecules}}\right]_{\text{type II}} = \frac{r^2}{4L(L + 2r)} \quad [1\text{-}1]$$

where r is the particle radius and L is the mean free path. At the nozzle entrance L = approx $3r$, while at the exit L = approx $65r$, so that the above ratio is less than 0.02 at the nozzle entrance and is exceedingly small at the exit. For an ideal collision the average energy exchange between molecules is a half of their initial energy difference, so that those molecules of type II which are hot will impart to type I molecules on the average, and at most, only a half of the temperature increment they (hot type II) received from their previous collision with the particle. Thus the error encountered when assuming all type I molecules are at the body temperature of the gas is at most 1 per cent at the nozzle inlet.

Since the ratio of the mean free path to the particle radius increases with distance toward the nozzle exit, the over-all errors should certainly be less than 1 per cent.

Since the above model is that of a single particle surrounded by hydrogen gas, it is necessary to take into account the effects on heat transfer of other carbon particles in close proximity to the single particle being considered. For the chamber conditions in the present example, the average distance d between particles ($r = 10^{-6}$ cm) is 15×10^{-6} cm or about 5 free paths separation beween particles. At the nozzle exit, the average d is 38×10^{-6}, the mean free path 65×10^{-6}. Thus the hydrogen to carbon mean free path here is nearly twice the average distance between carbon particles. However, with the kinetic theory of gases (8) one may show for the case being considered, for both nozzle exit and chamber, that hydrogen to hydrogen collisions are about 280 times more frequent than hydrogen to carbon particle collisions. It follows that in both cases, on the average, a hydrogen molecule

[7] It may be shown from the kinetic theory of gases (8) that for the solid-gas system under consideration the mean free path of a hydrogen molecule with reference to a carbon particle 10^{-6} cm in radius or larger is the same as the free path between two hydrogen molecules.

whose next collision is with a carbon has reached gas temperature. Thus the model of a single carbon particle in hydrogen gas is accurate for the case under consideration.

For solid particles 10^{-5} cm in radius and rocket conditions comparable to those of the example in which a particle 10^{-6} cm in radius was assumed, the ratio expressed by Equation [1-1] was 0.26 at the nozzle inlet. Since for an ideal collision the average energy exchange between molecules is half their initial energy difference, the error in assuming that all type I molecules are at the body temperature of the gas is at most 13 per cent, decreasing to less than 1 per cent at the exit. Hence, the heat transfer at the inlet should be too large by this same percentage. On the other hand, the conservative choice of the accommodation coefficient should more than compensate for this error.

APPENDIX 2

Derivation of Heat Flow Equation

Consider one solid particle in the solid-gas mixture. It follows from the definition of α that the amount of heat transferred from the particle to the gas in time dt is

$$dQ = \alpha S N_s c_v'(T_s - T_g)dt \quad \text{[2-1]}$$

where α is the thermal-accommodation coefficient, S is the surface area of the solid particle, N_s is the number of collisions per sec per cm^2 of particle surface area, and c_v' is the translational heat capacity per gas molecule.

With Equation [2-1] and the kinetic theory of gases (9), one obtains

$$dQ = \alpha r^2 c_v'' p\left[\frac{8\pi M}{RT_g}\right]^{1/2}(T_s - T_g)dt \quad \text{[2-2]}$$

Since Equation [2-2], when substituted into the usual energy equation of steady flow (6), gives an expression that is much too complex to integrate by practical means, it will be integrated directly with certain simplifying assumptions for use in a stepwise approximate calculation.

Consider a given time interval $t_i \leqq t \leqq t_f$ along the rocket axis, as shown in Fig. 5, and assume that for the given interval the factor p and the factor T_g appearing under the radical in [2-2] remain constant[8] and are given for the interval by their

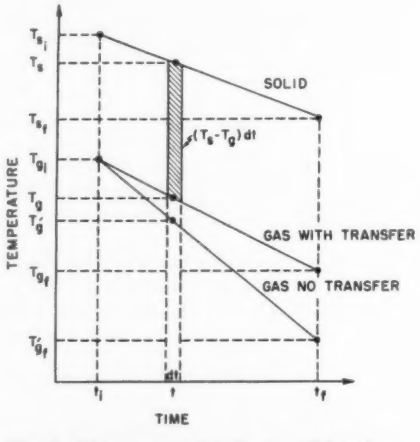

Fig. 5 Linear approximation to solid and gas temperatures over a given time interval

average values p and T_g, respectively; [2-2] then becomes

$$dQ = k(T_s - T_g)dt \quad \text{[2-3]}$$

where

$$k = \alpha r^2 c_v'' p\left[\frac{8\pi M}{RT_g}\right]^{1/2} \quad \text{[2-4]}$$

Now select a time increment dt at point t within the given time interval as shown in Fig. 5. In going from t_i to t, each solid particle loses an amount of heat Q given by

$$Q = m_s c_s(T_{si} - T_s) \quad \text{[2-5]}$$

In this time the gas will gain kinetic energy (KE) at the expense of the heat gained Q and its initial enthalpy. Thus

$$Q + m_g c_p(T_{gi} - T_g) = (\text{KE}) \quad \text{[2-6]}$$

where m_s is the mass of one solid particle. But if no heat were transferred to the gas from the solid and the gas expanded through the same area ratio interval defined by t_i and t in Fig. 5, the gas would gain kinetic energy (KE)$'$ given by

$$m_g c_p(T_{gi} - T_g') = (\text{KE})' \quad \text{[2-7]}$$

where $m_g = m_s/8$. Combining [2-6] and [2-7] and assuming the kinetic energy change in each case to be the same[9] gives

$$Q = m_g c_p(T_g - T_g') \quad \text{[2-8]}$$

where T_g' is the temperature of the gas at time t assuming that no heat is transferred to the gas after time t_i. Now for the given time interval the temperature of the gas T_g' may be expressed as a linear function of time. Then

$$T_g' = ft + g \quad \text{[2-9]}$$

where f and g are constants which may be evaluated at the boundary points of the interval. Equation [2-8] then becomes

$$Q = m_g c_p(T_g - ft - g) \quad \text{[2-10]}$$

Substituting Equations [2-10] and [2-5] into [2-3] gives

$$dQ = k\left[T_{si} - ft - g - Q\left(\frac{1}{m_s c_s} + \frac{1}{m_g c_p}\right)\right]dt \quad \text{[2-11]}$$

Making the substitutions

$$\left.\begin{aligned} D &= T_{si} - g \\ B &= \frac{1}{m_s c_s} + \frac{1}{m_g c_p} \end{aligned}\right\} \quad \text{[2-12]}$$

Equation [2-11] may be written

$$\frac{dQ}{dt} + kBQ = k(D - ft) \quad \text{[2-13]}$$

Using the integrating factor e^{kBt}, integrating, and evaluating at the boundary conditions, $t = 0$, $Q = 0$, $t = \Delta t$, and $Q = \Delta Q$, gives

$$\Delta Q = -\frac{f\Delta t}{B} + \left(\frac{D}{B} + \frac{f}{kB^2}\right)(1 - e^{-kB\Delta t}) \quad \text{[2-14]}$$

Evaluating f and g from Equation [2-9] by the boundary conditions: at $t = 0$, $T_g' = T_{gi}$, and at $t = \Delta t$, $T_g' = T_{gf}'$, gives

$$\left.\begin{aligned} g &= T_{gi} \\ f &= \frac{T_{gf}' - T_{gi}}{\Delta t} \end{aligned}\right\} \quad \text{[2-15]}$$

Substituting Equation [2-15] and [2-12] into [2-14] gives

$$\Delta Q = \frac{T_{gi} - T_{gf}'}{B} + \left[\frac{T_{si} - T_{gi}}{B} - \frac{T_{gi} - T_{gf}'}{kB^2\Delta t}\right][1 - e^{-kB\Delta t}] \quad \text{[2-16]}$$

[8] N_s is proportional to $p/\sqrt{T_g}$, so that this is equivalent to assuming a constant N_s for a given interval.

[9] Fig. 1 shows that (KE) and (KE)$'$ are nearly equal. Therefore, the error involved is a second order one and in any case is on the side of lower heat transfer.

It may be shown that

$$B = \frac{3a}{4\pi\rho_s r^3}\left(\frac{1}{ac_s} + \frac{1}{bc_p}\right) \quad \text{[2-17]}$$

while k is given by Equation [2-4].

Using the values $\rho_s = 2.25$ g/cm^3, $r = 10^{-6}$ cm, $a = 0.8889$, $b = 0.1111$, $c_s = 2.047 \times 10^7$ erg/(g)(°K), $c_p = 1.647 \times 10^8$ erg/(g)(°K), $\alpha = 0.1$, $c_v'' = 6.279 \times 10^7$ erg/(g)(°K), $M = 2$ g/mole, and $R = 8.315 \times 10^7$ erg/(mole)(°K), gives

$$B = 0.1034 \times 10^{11} \text{ °K/erg}$$

$$k = (4.883 \times 10^{-9} \text{ cm}^3/\text{sec °K}^{1/2})p/\sqrt{T_g}$$

APPENDIX 3

Specific Heat Ratio as a Function of Amount of Heat Transfer

For the given solid-gas system, if the solid temperature changes by dT_s, and the gas temperature changes by dT_g, the internal energy of the system will change by an amount dU given by

$$dU = a\,mc_s dT_s + b\,mc_v dT_g \quad \text{[3-1]}$$

Now if for a given interval dT_g/dT_s may be considered constant, then

$$\frac{dT_g}{dT_s} = \frac{\Delta T_g}{\Delta T_s} \quad \text{[3-2]}$$

$$dT_s = \frac{dT_g}{\Delta T_g/\Delta T_s} \quad \text{[3-3]}$$

Thus

$$dU = \left(\frac{a\,mc_s}{\Delta T_g/\Delta T_s} + b\,mc_v\right)dT_g \quad \text{[3-4]}$$

For the system, the specific heat c_v^* at constant volume is

$$c_v^* = \frac{1}{m}\left(\frac{\partial U}{\partial T_g}\right)_V = \frac{ac_s}{\Delta T_g/\Delta T_s} + bc_v = \frac{ac_s}{\Delta T_g/\Delta T_s} + b\left(c_p - \frac{R}{M}\right) \quad \text{[3-5]}$$

Similarly, the specific heat c_p^* at constant pressure for the system is

$$c_p^* = \frac{1}{m}\left(\frac{\partial H}{\partial T_g}\right)_p = \frac{ac_s}{\Delta T_g/\Delta T_s} + bc_p \quad \text{[3-6]}$$

Thus we define the specific heat ratio η for the system, which is dependent upon the amount of heat transferred between solid and gas phases, by

$$\eta = \frac{c_p^*}{c_v^*} = \frac{\left[\frac{ac_s}{(\Delta T_g/\Delta T_s)} + bc_p\right]}{\left[\frac{ac_s}{(\Delta T_g/\Delta T_s)} + bc_p\right] - \frac{bR}{M}} \quad \text{[3-7]}$$

which holds over the interval where $\Delta T_g/\Delta T_s$ may be considered constant. This concept of a specific heat ratio η is perfectly general for a solid-gas system and may be applied to the cases of complete and no heat transfer. For complete heat transfer, $\Delta T_g/\Delta T_s = 1$, and Equation [3-7] reduces to

$$\eta = \frac{ac_s + bc_p}{ac_s + bc_v} \quad \text{[3-8]}$$

which is the customary expression for the specific heat ratio of a solid-gas system.

For no heat transfer, $\Delta T_g/\Delta T_s = \infty$, and

$$\eta = \frac{c_p}{c_v} \quad \text{[3-9]}$$

which is the specific heat ratio for hydrogen alone.

APPENDIX 4

Equations of Flow

From the energy equation of steady flow it is readily shown that

$$v = \left[\frac{2bR}{M}\frac{\eta}{\eta - 1}(T_o - T_g)\right]^{1/2} \quad \text{[4-1]}$$

where T_o is the inlet temperature, v is the fluid velocity, and T_g the gas temperature at any position along the axis, and η is the ratio of specific heats defined by [3-7].

Combination of [4-1] with the equation of continuity, the gas law, and the relation

$$\frac{T_{g_1}}{T_{g_2}} = \left[\frac{p_1}{p_2}\right]^{(\eta-1)/\eta} \quad \text{[4-2]}$$

(where the subscripts refer to two positions along the nozzle axis) gives

$$\frac{A_1}{A_2} = \left[\frac{T_{g_2}}{T_{g_1}}\right]^{1/(\eta-1)}\left[\frac{T_o - T_{g_2}}{T_o - T_{g_1}}\right]^{1/2} \quad \text{[4-3]}$$

If A^* is taken as the throat area, then $T_{g_2} = T_{g_t} = 2T_o/(\eta + 1)$ (Reference 7) and Equation [4-3] becomes

$$\frac{A}{A^*} = \left[\frac{2}{\eta + 1}\frac{T_o}{T_g}\right]^{1/(\eta-1)}\left[\frac{\eta - 1}{\eta + 1}\frac{1}{1 - (T_g/T_o)}\right]^{1/2} \quad \text{[4-4]}$$

Thus by employing Equations [4-1], [4-2], and [4-4], complete data at any area ratio may be computed. The value of η is given by Equation [3-7].

APPENDIX 5

Heat Transfer from a Solid-Gas Directed Velocity Difference

To simplify the problem of heat transfer, it was assumed that the solid and gas exhaust components were in directed or stream velocity equilibrium. Thus heat is assumed to be transferred only as a result of random collisions of gas molecules with the solid particles. It is the purpose of the following to estimate the relative importance of heat transferred from solid to gas resulting from a directed velocity difference between solid and gas.

Since the heat transferred from solid to gas is directly proportional to the number of collisions of gas molecules with the solid particles

$$\frac{q_D}{q_R} = \frac{N_D}{N_R} \quad \text{[5-1]}$$

where q_D is rate of heat transfer from directed velocity collisions, q_R is that from random collisions, and N_D and N_R are the collisions per second from directed and random velocity collisions, respectively.

If there are N_r molecules per unit volume and if the directed velocity difference between gas and solid is Δv, then the number of collisons per second from directed velocity difference is given by

$$N_D = \pi r^2 N_r \Delta v \quad \text{[5-2]}$$

where r is the radius of the particle.

From the gas law and the kinetic theory of gases (9) it is easily shown that

$$\frac{q_D}{q_R} = \left[\frac{\pi M}{8RT_g}\right]^{1/2}\Delta v \quad \text{[5-3]}$$

Since the ratio q_D/q_R is inversely proportioned to $\sqrt{T_g}$, the exit temperature of 1300 K is taken. An analysis for carbon particles 10^{-5} cm in radius showed a maximum relative

velocity of 4×10^4 cm/sec (throat). It should be much less for particles 10^{-6} cm in radius. In any case the ratio q_D/q_R is no greater than 0.11 and on the average probably much less.

Thus the assumption that no velocity difference exists between solid and gas should not appreciably affect heat transfer results.

Acknowledgments

This work was carried out under the sponsorship of the Department of the Navy, Bureau of Ordnance. The authors wish to thank the following personnel of Experiment Incorporated: K. C. Rathbun, C. P. Talley, and W. E. Rice for helpful discussions; and W. E. Rice, F. R. Scott, and H. F. Calcote for a critical reading of the manuscript.

References

1 Maxwell, W. R., Dickinson, W., and Caldin, E. F. "Adiabatic Expansion of a Gas Stream Containing Solid Particles," *Aircraft Engineering*, vol. 18, Oct. 1956, pp. 350–351.

2 Altman, D., and Carter, James M., "Combustion Processes" (Lewis, Pease, and Taylor, editors), Princeton University Press, Princeton, 1956, p. 52.

3 Smith, W. R., "Carbon Black," Godfrey L. Cabot, Boston, 1949.

(*Continued on page 1090*)

ICAO Standard Atmosphere Extension

TWENTY-THREE United States scientific and engineering organizations are adopting a new extension to the 20 kilometer ICAO Standard Atmosphere (the accepted U. S. standard). Prepared under the co-sponsorship of the U. S. Weather Bureau and the Geophysics Research Directorate of the Air Force Cambridge Research Center, the extension provides a table of values (Table 1) of atmospheric parameters up to 300 kilometers.

Two of the values, molecular scale temperature and geopotential altitude, are shown graphically as T_M vs. H (Fig. 1).

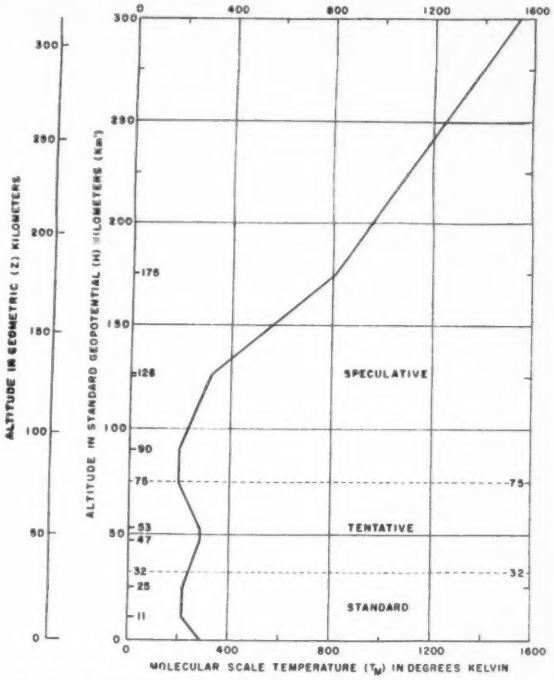

Fig. 1 Molecular scale temperature vs. geopotential altitude

$T_M \equiv (T/M)M_0 = T(M_0/M)$

(T_M = molecular scale temperature; T = real kinetic temperature; M = mean molecular weight; M_0 = mean molecular weight at sea level; 0–90 gpkm; $T = T_M$)

Table 1. United States extension to the standard atmosphere

H, m′	Z, m	L, °K/m′	T_M, °K	T, °K	M, gr/mole	P, mb
0.00	0.00		288.16	288.16	28.966	1.01325×10^3
		−0.0065				
11,000.0	11,019		216.66	216.66	28.966	2.2632×10^2
		0.0000				
[a]20,000.0	20,063		216.66	216.66	28.966	5.4748×10^1
		0.0000				
25,000.0	25,099		216.66	216.66	28.966	2.4886×10^1
		0.0030				
[a]32,000.0	32,162		237.66	237.66	28.966	8.6776×10^0
		0.0030				
47,000.0	47,350		282.66	282.66	28.966	1.2044×10^0
		0.0000				
53,000.0	53,446		282.66	282.66	28.966	5.8320×10^{-1}
		−0.0039				
75,000.0	75,895		196.86	196.86	28.966	2.4521×10^{-2}
		0.0000				
90,000.0	91,294		196.86	196.86	28.966	1.8154×10^{-3}
		0.0035				
126,000.0	128,548		322.86	278.88[b]	25.02[b]	1.4510×10^{-5}
		0.0100				
175,000.0	179,954		812.86	686.13[b]	24.45[b]	6.1895×10^{-7}
		0.0058				
300,000.0	314,859		1537.86	1024.67[b]	19.30[b]	1.4473×10^{-8}

Z = altitude in geometric meters
H = altitude in geopotential meters
L = temperature lapse rate in Kelvin degrees per geopotential meter
T_M = molecular scale temperature in degrees Kelvin
T = real kinetic temperature in degrees Kelvin
M = molecular weight in grams per mole
P = pressure in millibars

[a] Top of current ICAO Standard and top of recommended extension for standardization—no discontinuity in temperature-height curve.

[b] Approximate values subject to minor revision depending upon recomputation of M above 90 km.

Technical Notes

Stagnation Point Heat Transfer for Hypersonic Flow

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Nomenclature

h = enthalpy
i = dimensionless enthalpy = h/h_B
i^* = dimensionless reference enthalpy, Equation [3]
k = ratio of free stream density to density behind the normal shock
M = Mach number
p = pressure
Pr = Prandtl number = viscosity $\times$ $\frac{\text{specific heat}}{\text{thermal conductivity}}$
q = compressible stagnation heat transfer rate
Q = the ratio $q/\sqrt{u_o'}$
R_N = radius of the nose
R = gas constant
s = surface distance around nose
T = temperature
u = velocity
u' = velocity gradient = du/ds
γ = ratio of specific heats
λ = factor in heat transfer equation, Equation [13]
μ = viscosity
ρ = density

Subscripts

∞ = free stream
o = stagnation
w = wall
B = base (at T_B = 400 R)
i = incompressible

Superscript

* = quantity evaluated at reference enthalpy

Introduction

IT IS the purpose of this note to present a design method for obtaining stagnation point heat transfer in hypersonic flow. The heat transfer equation introduces real gas effects through use of a real gas reference enthalpy and fitted curve for stagnation point velocity gradient. Use of the reference enthalpy method permits agreement of ±5 per cent with the compressible dissociated stagnation point heat transfer obtained from numerical integration of the equations of motion and energy. The derived equation for heat transfer is a function only of free stream Mach number, free stream pressure, and body nose radius.

Analysis

The incompressible stagnation point heat transfer equation, given by Sibulkin (1),[2] is

$$q_i = 0.763\sqrt{\rho\mu}\sqrt{u_o'}(h_o - h_w) \quad [1]$$

evaluated at $Pr = 1$.

An incompressible equation like [1] can be used to obtain compressible heat transfer if it is possible to account for the effects of compressibility on the air property values and the stagnation point velocity gradient appearing therein. These two problems can be treated separately since the velocity gradient may be determined without reference to the boundary layer equations.

Compressibility, however, affects the boundary layer profiles and would effectively change the constant in Equation [1] to a function of Mach number and wall-to-stream temperature ratio. Rather than change the constant for each flow problem treated, it has been the custom to evaluate the air properties at different temperature levels, accounting for the compressibility effects in this manner.

Various temperature levels have been suggested at which to evaluate the properties $\rho\mu$. Among them are the wall temperature, the stream temperature, an average temperature, or some other reference temperature determined from exact solutions. The best approximation to flat plate compressible heat transfer has been obtained by evaluating $\rho\mu$ at the reference temperature, which is a function of local Mach number and wall-to-stream temperature ratio. A complete discussion of this technique, beyond the scope of this note, may be found in (2).

It has been well established (2) that compressibility effects for flat plate laminar flow can be introduced through use of the reference temperature. It is assumed that this method will apply to stagnation point flow as well. If it is further assumed that real gas effects are included through use of a reference enthalpy, rather than a reference temperature, and the proper air properties, then Equation [1] may be used to determine stagnation point heat transfer in hypersonic flow. It will be seen later that these latter assumptions are apparently justified.

In order to simplify the analysis several further assumptions will be made. Any one of these may be modified without invalidating the following development.

1 Newtonian flow equations apply for surface pressure and stagnation point velocity gradient.
2 $M_\infty \gg 1$ and $h_o \gg h_w$; i.e., the wall is cool compared to the stream.
3 Free stream temperature T_∞ = 400 R = T_B.
4 $Pr = 1$.
5 The body shape in the stagnation region is spherical.

Note that modification of assumption 2 permits extension of this analysis to supersonic flow. The curve-fitted equations for u_o' and $\rho\mu$ also permit this extension.

On the basis of these assumptions, the compressible stagnation point heat transfer becomes

$$q = 0.763\sqrt{\rho^*\mu^*}\sqrt{u_o'}h_o \quad [2]$$

for hypersonic flow. The dimensionless reference enthalpy, defined in Reference (2) reduces to

$$i^* = 0.5(i_o + i_w)$$

at the stagnation point. From assumption 2

$$i^* = 0.5i_o \quad [3]$$

where $i = h/h_B$.

The stagnation enthalpy, determined from free stream conditions, is

$$\frac{h_o}{h_\infty} = 1 + \frac{\gamma_\infty - 1}{2} M_\infty^2$$

Received Sept. 14, 1956.
[1] Staff Scientist, Scientific Research Laboratory.
[2] Numbers in parentheses indicate References at end of paper.

EDITOR'S NOTE: This section of JET PROPULSION is open to short manuscripts describing new developments or offering comments on papers previously published. Such manuscripts are published without editorial review, usually within two months of the date of receipt. Requirements as to style are the same as for regular contributions (see masthead page of this issue).

For $h_\infty = h_B$ (assumption 3) and $M_\infty \gg 1$

$$i_o = \frac{\gamma_\infty - 1}{2} M_\infty^2 \quad \ldots\ldots [4]$$

and, from Equation [3], for $\gamma_\infty = 1.4$

$$i^* = 0.1 M_\infty^2 \quad \ldots\ldots [5]$$

so that Equation [2] becomes (for $h_B = 96.8$ Btu/lb)

$$q = 0.763 \times 96.8 \times 0.2 \sqrt{\rho^*\mu^*}\sqrt{u_o'}\, M_\infty^2 \quad \ldots\ldots [6]$$

Examination of Equations [5] and [6] shows it would be desirable to express $\rho^*\mu^*$ (or i^*) and u_o' as functions of given (free stream) conditions. It is possible to do this through use of fitted curves and assumptions 1 through 5.

The Air Properties

For moderate supersonic Mach numbers the values of $\rho^*\mu^*$ to be used in Equation [6] are comparatively well defined. As the air temperature increases with speed, however, the various constituents become dissociated and complex chemical reactions occur. In this analysis the air will be assumed to be in dissociation equilibrium. The density and viscosity selected for use in this analysis are associated with the most recent complete set of air properties (3). While the thermal properties (p, T, ρ, h) have subsequently been revised (4) the transport properties have yet to be computed. It is suggested that when new transport properties become available they be incorporated into the analysis in a manner similar to the following procedure.

Fig. 1 shows the variation of $\rho\mu/\rho_B\mu_B$ with enthalpy. The pressure dependency of density is incorporated into the base density by the expression

$$\rho_B = \frac{p_{(\text{local})}}{RT_B}$$

where $T_B = 400$ R. The variation of $\rho\mu/\rho_B\mu_B$ with pressure due to dissociation is slight (within ±6 per cent from 0.1 to 10 atm) so the curve for $p = 1$ atm is plotted in Fig. 1. A good approximation to the curve of Fig. 1 is given by

$$\rho\mu = \rho_B\mu_B(i)^{-0.28}$$

or, in this particular case, from Equation [5]

$$\rho^*\mu^* = 1.9\rho_B\mu_B M_\infty^{-0.56} \quad \ldots\ldots [7]$$

Now, the above equation is still a function of local flow properties through the density ρ_B. The local pressure, in this case the stagnation pressure, can be removed through use of the Newtonian flow equation at hypersonic Mach numbers (7, p. 265)

$$p_o = p_\infty + \gamma_\infty M_\infty^2 p_\infty \backsimeq \gamma_\infty M_\infty^2 p_\infty$$

so that

$$\rho^*\mu^* = \frac{1.9\gamma_\infty \mu_B}{RT_B} p_\infty M_\infty^{1.44} \quad \ldots\ldots [8]$$

The Velocity Gradient

The stagnation point velocity gradient for hypersonic flow on a sphere is given by the constant-density Newtonian flow approximation developed by Li and Geiger (5)

$$u_o' = \frac{u_\infty}{R_N}\sqrt{k(2-k)} \quad \ldots\ldots [9]$$

where k is the ratio of free stream density to density behind the normal shock. Values of $\sqrt{k(2-k)}$ are given in Fig. 2 for

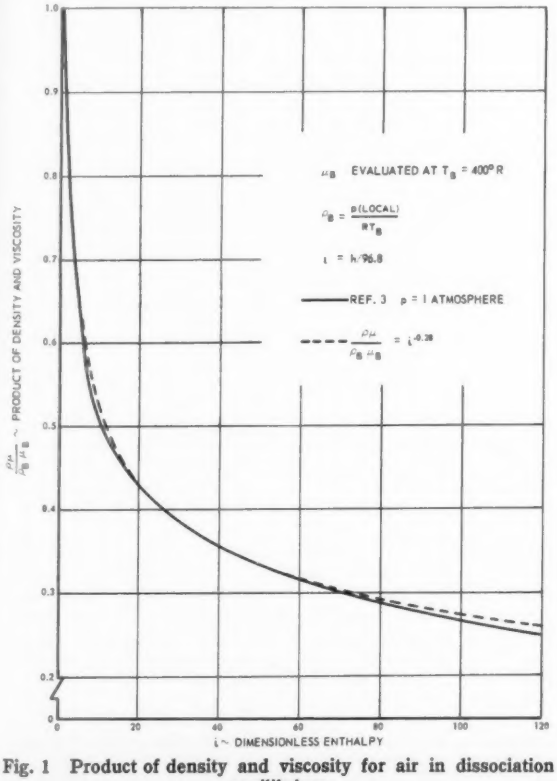
μ_B EVALUATED AT T_B = 400° R
$\rho_B = \frac{p(\text{LOCAL})}{RT_B}$
$i = h/96.8$
REF. 3 p = 1 ATMOSPHERE
$\frac{\rho\mu}{\rho_B\mu_B} = i^{-0.28}$
$\frac{\rho\mu}{\rho_B\mu_B}$ ~ PRODUCT OF DENSITY AND VISCOSITY
i ~ DIMENSIONLESS ENTHALPY

Fig. 1 Product of density and viscosity for air in dissociation equilibrium

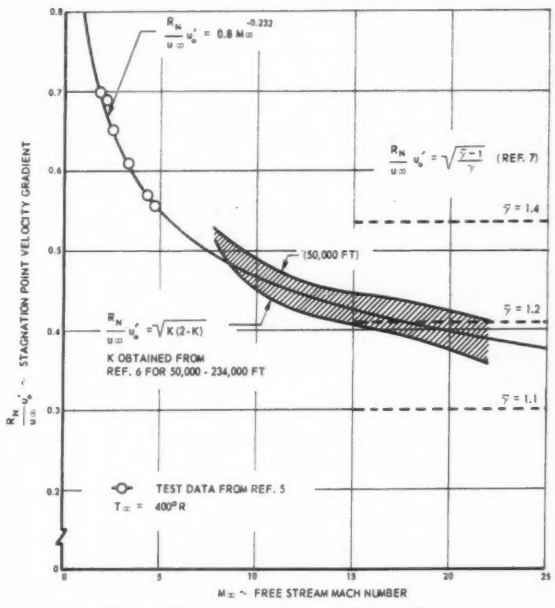
$\frac{R_N}{u_\infty} u_o' = 0.8 M_\infty^{-0.232}$
$\frac{R_N}{u_\infty} u_o' = \sqrt{\frac{\bar\gamma - 1}{\bar\gamma}}$ (REF. 7)
$\bar\gamma = 1.4$
(50,000 FT)
$\bar\gamma = 1.2$
$\frac{R_N}{u_\infty} u_o' = \sqrt{K(2-K)}$
K OBTAINED FROM REF. 6 FOR 50,000 - 234,000 FT
$\bar\gamma = 1.1$
TEST DATA FROM REF. 5
T_∞ = 400° R
$\frac{R_N}{u_\infty} u_o'$ ~ STAGNATION POINT VELOCITY GRADIENT
M_∞ ~ FREE STREAM MACH NUMBER

Fig. 2 Stagnation point velocity gradient

the normal shock solution of (6), which is based on the recent air properties of (4). Fig. 2 shows that u_o' can be approximated by

$$u_o' = \frac{0.8}{R_N} u_\infty M_\infty^{-0.232} = \frac{0.8}{R_N}\sqrt{\gamma_\infty RT_\infty}\, M_\infty^{+0.768} \quad \ldots [10]$$

neglecting the variation in $\sqrt{k(2-k)}$ with free stream pressure. The curve given by Equation [10] also agrees with the low speed test data of (5).

Another method of obtaining u_o' for hypersonic flow is to consider use of an effective γ rather than use of real gas air properties. Lees (7) suggests the formula, which at high Mach numbers reduces to

$$u_o' \backsimeq \frac{u_\infty}{R_N}\sqrt{\frac{\bar\gamma - 1}{\bar\gamma}} \quad \ldots\ldots [11]$$

where $\bar{\gamma}$ is suggested to vary between 1.1 to 1.2 for high temperature flow. This equation is also shown in Fig. 2 for $\bar{\gamma} = 1.1$, 1.2, and 1.4. It can be seen that using a constant value of $\bar{\gamma}$ restricts the formula for u_o' to a given Mach number region. For this reason [10], which is applicable over a wide range of Mach numbers, is recommended for general use. In specific instances where the Mach number range permits use of a constant $\bar{\gamma}$, Equation [11] is recommended on the basis of its simplicity.

Stagnation Point Heat Transfer

The use of Equations [8, 10] now allow the heat transfer, Equation [6], to be expressed solely as a function of free stream Mach number, pressure, and nose radius. After the constants are evaluated, with $T_\infty = T_B = 400$ R, then

$$q = 0.0145\, M_\infty^{3.1} \sqrt{\frac{p_\infty}{R_N}} \quad \ldots\ldots\ldots\ldots [12]$$

The restrictions on Equation [12] are that $M_\infty \gg 1$, a cooled wall, and free stream temperature $T_\infty = 400$ R. These conditions could correspond to flight in the isothermal altitudes. As mentioned before, modification of assumption 2 will allow extension of this method to supersonic flow also. The final equation for heat transfer will not be so simple in form, since some terms neglected for hypersonic flow should be retained for the supersonic case.

Comparison With Other Solutions

Unfortunately, there is no experimental comparison for Equation [12], since test data in this flight regime are not available. In most cases of numerical solutions for the compressible stagnation point, the determination of $\rho\mu$ and u_o' are left in the equation as parameters to be determined by the reader. Thus the only verification of Equation [12] which can be offered is to check the validity of the use of a reference enthalpy, i.e., to determine how well the method approximates the conditions of compressibility and dissociation.

The reference enthalpy method can be tested in this way by inserting the curve-fitted equation for $\rho^*\mu^*$ (Equation [7]) into the heat transfer equation (Equation [2]) and comparing with the numerical solution of Mark (8). This solution of the compressible stagnation point boundary layer includes use of the dissociated air properties of (3). In Mark's equation

$$q = \left\{ \frac{\rho_w \mu_w / \rho_B \mu_B \, \lambda}{\sqrt{\rho_o \mu_o / \rho_B \mu_B} \; Pr_w} \right\} \sqrt{u_o'}\, h_o \sqrt{\rho_B \mu_B}$$

Equation [2] can be written

$$q = \{0.763 \sqrt{1.9}\, M_\infty^{-0.28}\} \sqrt{u_o'}\, h_0 \sqrt{\rho_B \mu_B}$$

The terms in brackets should compare and will indicate the effectiveness of the reference enthalpy in approximating compressible heat transfer. The ratio

$$\frac{q(i^*)}{q(\text{Mark})} = \frac{0.763 \sqrt{1.9} \sqrt{\rho_o \mu_o / \rho_B \mu_B}\, Pr_w}{\lambda M_\infty^{+0.28} (\rho_w \mu_w / \rho_B \mu_B)} \quad \ldots\ldots [13]$$

is plotted in Fig. 3 for the range of flight velocities covered by (8). The agreement is within ±5 per cent for the three wall temperature values given by Mark. This tends to substantiate the assumptions made previously that the reference enthalpy method can be used at the stagnation point, and furthermore that it accounts for real gas effects on the compressible boundary layer.

Another calculation which can be made points out the effects of compressibility and dissociation on the stagnation point boundary layer heat transfer. A plot of such a calculation also offers a simple graphical method of obtaining heat transfer from a standard solution. The function $Q = q/\sqrt{u_o'}$ can be determined from Equations [2, 7] for compressible flow. The incompressible $Q_i = q_i/\sqrt{u_o'}$ is given in Equation [1],

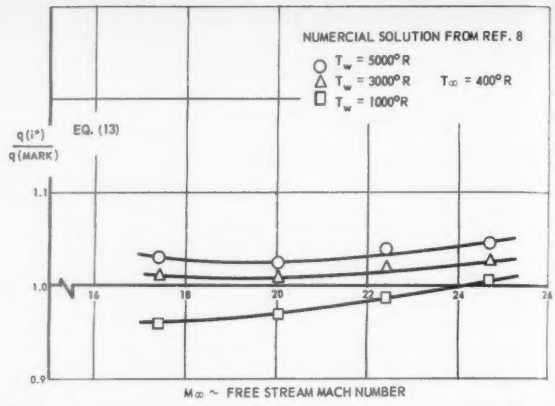

Fig. 3 Comparison of numerical and approximate compressible heat transfer solutions for air in dissociation equilibrium

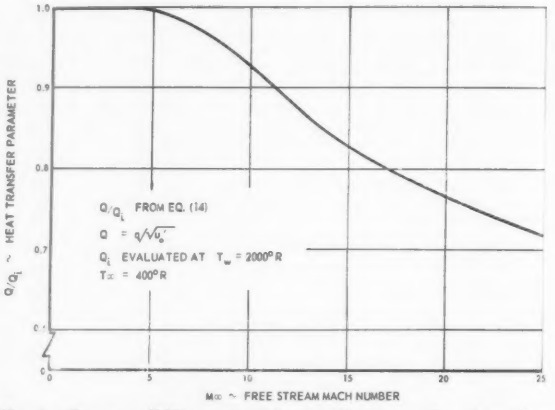

Fig. 4 Compressibility and real gas effects on the stagnation point heat transfer parameter

evaluated at a given wall temperature T_w. The ratio

$$\frac{Q}{Q_i} = \frac{\sqrt{1.9}\, M_\infty^{-0.28}}{\sqrt{\rho_w \mu_w / \rho_B \mu_B}} \quad \ldots\ldots\ldots\ldots [14]$$

is plotted in Fig. 4 for $T_w = 2000$ R. It indicates the effect of compressibility and dissociation on the boundary layer. Since Q_i is comparatively easy to evaluate, Fig. 4 presents a rapid method of obtaining Q, which with Equation [10] gives the value of compressible heat transfer.

It can be seen in Fig. 4 that evaluation of the air properties at the wall conditions could result in overestimation of heat transfer by as much as 30 per cent at Mach 20. Since Equation [1] is sometimes used to obtain engineering estimates the possible error induced should be kept in mind.

References

1 Sibulkin, M., "Heat Transfer Near the Forward Stagnation Point of a Body of Revolution," *Journal of the Aeronautical Sciences*, vol. 19, 1952, pp. 570–571.

2 Eckert, E. R. G., "Survey on Heat Transfer at High Speeds," Wright Air Development Center TR 54-70, 1954.

3 Romig, Mary F., and Dore, Frank J., "Solutions of the Compressible Laminar Boundary Layer Including the Case of a Dissociated Free Stream," Convair Report ZA-7-012, 1954.

4 Hilsenrath, Joseph, and Beckett, Charles W., "Thermodynamic Properties of Argon-Free Air (0.78847 N_2, 0.21153 O_2) to 15,000°K," National Bureau of Standards Report 3991, 1955.

5 Li, Ting-Yi, and Geiger, Richard, "Stagnation Point of a Blunt Body in Hypersonic Flow," Presented at the IAS 24th Annual Meeting, Preprint no. 629, 1956.

6 Romig, Mary F., "The Normal Shock Solution for Air in Dissociation Equilibrium," *Journal of the Aeronautical Sciences*, vol. 23, 1956, pp. 185–186.

7 Lees, Lester, "Laminar Heat Transfer over Blunt-Nosed

Bodies at Hypersonic Flight Speeds," JET PROPULSION, vol. 26, April 1956, pp. 259–269.

8 Mark, R. M., "Compressible Laminar Heat Transfer Near the Stagnation Point of Blunt Bodies of Revolution," Convair Report ZA-7-016, 1955.

Comments on "Flight Measurements of Aerodynamic Heating and Boundary Layer Transition on the Viking 10 Nose Cone"[1]

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Nomenclature

C_f = friction factor
Nu = Nusselt number
Pr = Prandtl number
Re = Reynolds number
St = Stanton number
T = absolute temperature

Subscripts

w = wall
s = stream immediately outside boundary layer
r = recovery

Superscript

$*$ = reference condition

Introduction

THE purpose of this note is to present a method of correlating Viking 10 aerodynamic heating data having the following advantages: (a) The method has been used successfully to correlate other aerodynamic heating data (cf., e.g., 2)[3]; and (b) the physical description of the fluid flow and heat transfer phenomena forming the basis for this method is more delimiting than the physical description forming the basis for the method of Reference (1). It is believed that this method is applicable to a wider range of the variables than the method of (1). The several features discussed in this note, although not original with the writer (cf., e.g., 2) have not been seen in previous correlations of the Viking 10 data.

Correlation of Turbulent Flow Data

In (1) the experimentally determined dependence of the Nusselt number on the Reynolds number was compared, for turbulent flow, with the equation

$$Nu = 0.029\, Re^{0.8}\, Pr^{1/3} \quad \ldots\ldots [1]$$

In terms of the Stanton number, this equation is written in the form

$$\frac{Nu}{Re\, Pr} = St = \frac{0.029}{Re^{0.2}} \frac{1}{Pr^{2/3}} \quad \ldots\ldots [2]$$

or, since the factor $0.029/Re^{0.2}$ is approximately the local friction coefficient for turbulent flow along a flat plate as given by the Blasius equation, in the form

$$St = \frac{C_f}{2} \frac{1}{Pr^{2/3}} \quad \ldots\ldots [3]$$

This equation was used originally by Colburn (3) in 1933 to correlate data for heat transfer from a flat plate to a turbulent boundary layer. It is an expression of the analogy which Reynolds postulated to relate heat transfer and momentum transfer in shear flows, modified to describe effects of moderate deviations of the Prandtl number from unity. One would expect this analogy to hold as well for flows over cones as for flows over flat plates, although one would not expect the magnitudes of the friction coefficients and the Stanton numbers to be equal for the two flows. As is the situation for flow along a flat plate, fluid properties and flow parameters immediately outside the boundary layer on a cone do not vary in the direction of fluid flow. However, contrary to the situation for flow along a flat plate, the fluid within the boundary layer on a cone is spread peripherally as the fluid flows back along the cone. This peripheral spread of the fluid results in a thinning of the boundary layer. Analytical calculations and experimental data both indicate that, for turbulent flows, this thinning of the boundary layer causes the friction coefficient at a distance L from the apex of a cone to be equal to the friction coefficient at a distance $L/2$ from the leading edge of a flat plate, provided that flow conditions immediately outside the boundary layer are the same for the cone and for the flat plate (cf. 4, 5, and 6). Consequently, it would seem reasonable, when applying the Colburn equation to flows over cones, to modify it to account for this increase in the friction coefficient.

If fluid properties vary appreciably through the boundary layer, then the Colburn equation has been found to correlate the data surprisingly well if the fluid properties are evaluated at a "reference" temperature which is a weighted combination of recovery temperature, wall temperature, and temperature outside the boundary layer (cf. 2 and 7). It seems worth while, therefore, to try correlating the Viking data using one of the suggested "reference" temperatures.

If the Colburn equation is to be applied to flows at Reynolds numbers exceeding 10^7, then a third modification of this equation would improve the correlation of the data. Since the Blasius equation

$$\frac{C_f}{2} = \frac{0.0296}{Re^{0.2}} \quad \ldots\ldots [4]$$

gives friction factors which are too low for Reynolds numbers exceeding 10^7, and since equations such as the Schultz-Grunow equation

$$\frac{C_f}{2} = \frac{0.185}{(\log_{10} Re)^{2.584}} \quad \ldots\ldots [5]$$

represent measurements very well for Reynolds numbers up to 10^9, the Colburn equation would have greater usefulness if the friction factor is given by a relation such as Equation [5].

Taking into account these three features, one now obtains a modified Colburn equation

$$Nu^* = \frac{0.185}{[\log_{10} (Re^*/2)]^{2.584}} Re^* Pr^{*1/3} \quad \ldots\ldots [6]$$

or, in terms of the Stanton number

$$St^* = \frac{0.185}{[\log_{10} (Re^*/2)]^{2.584}} \frac{1}{Pr^{*2/3}} \quad \ldots\ldots [7]$$

where the asterisk indicates that fluid properties are to be evaluated at a "reference" temperature. As a check on the agreement of this equation with Viking 10 data, Nusselt and Reynolds numbers were recalculated using turbulent flow data for stations NE 26, NE 32, and NE 38, evaluating fluid properties at the "reference" temperature suggested by Eckert (2)

$$T^* = 0.50T_w + 0.28T_s + 0.22T_r \quad \ldots\ldots [8]$$

(Tabular data were obtained from Reference 8.) The modified Colburn equation appears to correlate the data as well as does the original Colburn equation (see Figs. 1 and 2). An examination of the calculations reveals that (in the range of parameters encountered in this flight) the 15 per cent increase in the aerodynamic heating caused by the thinning of the boundary layer on the conical body (taken into account by dividing the Reynolds number by 2) is compensated largely by the decrease in the aerodynamic heating caused by the variation of fluid properties in the boundary layer (taken into account by evaluating the fluid properties at a

Received Oct. 8, 1956.

[1] Reference (1).

[2] Formerly, Aerothermodynamics Group Leader, Aerophysics Development Corp. Presently, Associate Research Engineer, University of California, Los Angeles. Mem. ARS.

[3] Numbers in parentheses indicate References at end of paper.

"reference" temperature). This compensation does not exist usually.

Correlation of Laminar Flow Data

In Reference (1) the experimentally determined dependence of the Nusselt number on the Reynolds number was compared (for laminar flow) with the equation[4]

$$Nu = 0.51\sqrt{Re} \quad \ldots\ldots\ldots\ldots\ldots\ldots [9]$$

Since good correlation of aerodynamic heating data has been realized also for laminar flows if fluid properties are evaluated at a "reference" temperature (2), it would seem reasonable to attempt correlating the Viking data for laminar flows using such a "reference" temperature. Therefore, Nusselt and Reynolds numbers were recalculated using laminar flow data for stations SW 26, SW 32, and SW 38, evaluating fluid properties again at the "reference" temperature suggested by Eckert and given as Equation [8]. In the range of parameters encountered in the Viking 10 flight, evaluating fluid properties at the "reference" temperature appears to correlate the data as well as evaluating the fluid properties at the temperature outside the boundary layer (see Figs. 3 and 4).

[4] Equation [9] is a simplified expression of the Reynolds analogy restricted to fluids with Prandtl number of 0.7 and to laminar flows on cones

$$\frac{Nu}{Re\,Pr} = St = \frac{C_f}{2}\frac{1}{Pr^{2/3}} = \frac{0.332}{\sqrt{Re/3}}\frac{1}{0.7^{2/3}}$$

The Reynolds number was divided by 3 in the expression for the friction factor since, for laminar flow, the friction coefficient at a distance L from the apex of a cone has been shown to be equal to the friction coefficient at a distance $L/3$ from the leading edge of a flat plate, flow conditions immediately outside the boundary layer being the same (cf. Reference 9).

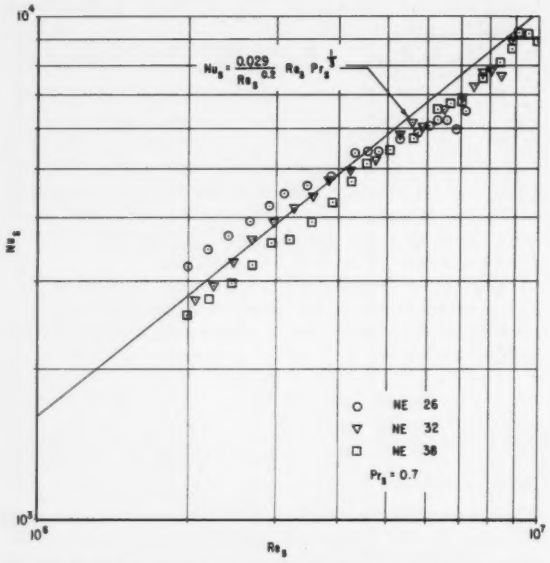


Fig. 1 Local Nusselt number vs. local Reynolds number for turbulent flow (three-dimensional nature of flow ignored, fluid properties evaluated at temperature outside boundary layer, Blasius friction factor)

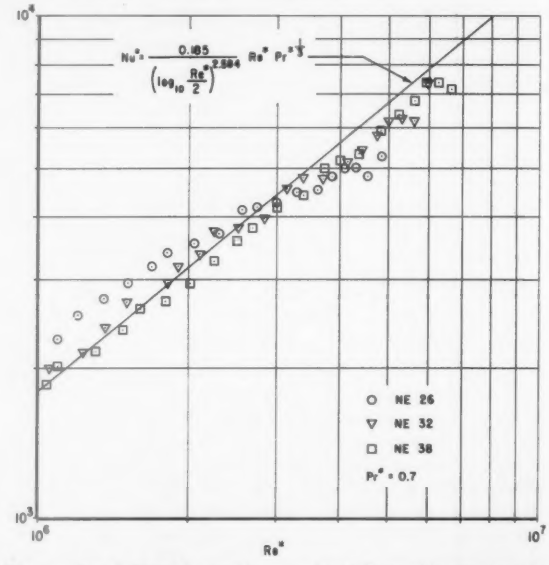


Fig. 2 Local Nusselt number vs. local Reynolds number for turbulent flow (three-dimensional nature of flow considered, fluid properties evaluated at "reference" temperature, Schultz-Grunow friction factor)

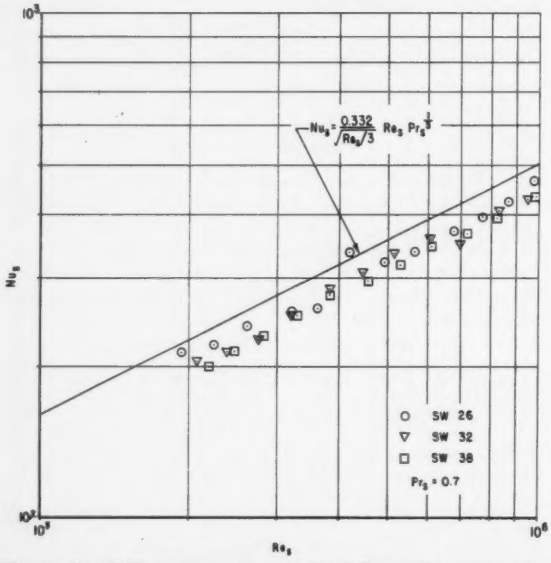


Fig. 3 Local Nusselt number vs. local Reynolds number for laminar flow (fluid properties evaluated at temperature outside boundary layer)

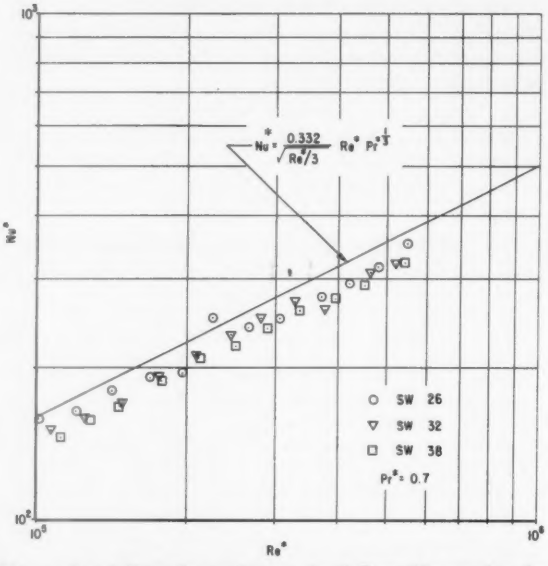


Fig. 4 Local Nusselt number vs. local Reynolds number for laminar flow (fluid properties evaluated at "reference" temperature)

Summary

Heat transfer data obtained with the Viking 10 have been correlated taking into account (a) variation of fluid properties with temperature in the boundary layer, and (b) effect of three-dimensional nature of flows over cones. The present correlation is believed to be applicable to a wider range of the variables than is the correlation presented in Reference (1).

References

1 Snodgrass, R. B., "Flight Measurements of Aerodynamic Heating and Boundary Layer Transition on the Viking 10 Nose Cone," JET PROPULSION, vol. 25, Dec. 1955, pp. 701–706.

2 Eckert, E. R. G., "Engineering Relations for Friction and Heat Transfer to Surfaces in High Velocity Flow," *Journal of the Aeronautical Sciences*, vol. 22, 1955, pp. 585–587.

3 Colburn, A. P., "A Method of Correlating Forced Convection Heat-Transfer Data and a Comparison with Fluid Friction," *Transactions of the American Institute of Chemical Engineers*, vol. 29, 1933, pp. 174–210.

4 Gazley, C., "Theoretical Evaluation of the Turbulent Skin Friction and Heat Transfer on a Cone in Supersonic Flight," Project Hermes Report R49A052, U. S. Army Ordnance Dept., Nov. 1949.

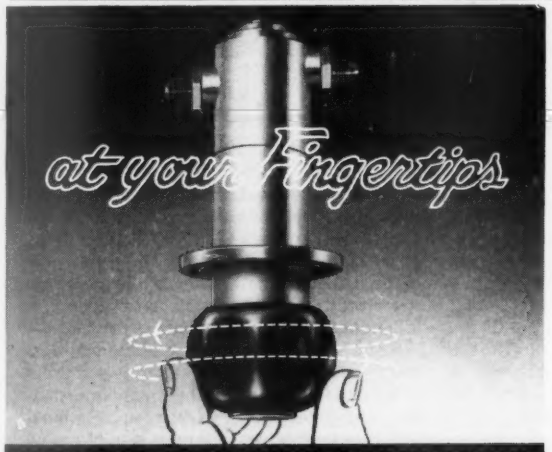
5 Van Driest, E. R., "Turbulent Boundary Layer on a Cone in a Supersonic Flow at Zero Angle of Attack," *Journal of the Aeronautical Sciences*, vol. 19, 1952, pp. 55–57.

6 DeCoursin, D. G., Bradfield, W. S., and Sheppard, J. J., "Aerodynamic Heating and Heat Transfer Phenomena at Mach Numbers 2.7 Through 5.7," WADC TR 53-379, Feb. 1954.

7 Sommer, S. C., and Short, Barbara J., "Free-Flight Measurements of Skin Friction of Turbulent Boundary Layers with High Rates of Heat Transfer at High Supersonic Speeds," *Journal of the Aeronautical Sciences*, vol. 23, 1956, pp. 536–542.

8 Snodgrass, R. B., "Flight Measurements of Aerodynamic Heating and Boundary-Layer Transition on the Viking 10 Nose Cone," Naval Research Lab. Report 4531, June 1955.

9 Hantzsche, W., and Wendt, H., "The Laminar Boundary Layer on a Circular Cone at Zero Incidence in a Supersonic Stream," Jahrbuch 1941 der Deutschen Luftfahrtforschung. Also RAND Translation no. RAT-6, Nov. 1947.



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Space Flight Notes

Kurt R. Stehling, Naval Research Laboratory, *Contributor*

Space Travel and Relativity
or How to Keep From Growing Old

WITH man's first hesitant step into space—Vanguard—not yet accomplished, there are many brave souls whose impatience drives them to speculation of travel beyond the solar system and into the interstellar ocean.

Such speculation is desirable if it does not interfere with the work at hand; and it is usually many generations beyond contemporary engineering feasibility. However, the dreaming must be tempered with a modicum of reality and awareness of certain fundamental limitations which are not gracious enough to vanish even before the most sanguine dreamer.

One limitation of interstellar space travel stands out above all others (and there are many): the fantastic distances between the solar system and even our nearest neighbors in space, such as the Centaur group of stars of which Alpha Centauri is visible to the unaided eye. A beam of light leaving the earth requires four years (earth time) to reach this star. Therefore, a space vehicle leaving the solar system at the speed of light, 186,000 miles/sec, would return in not less than eight years if no change of velocity or stopping were assumed. This statement beggars three others: the rather low probability, first, of a vehicle at all approaching the speed of light even in overdrive, and, secondly, of maintaining its integrity in the garbage-cluttered domain of space; thirdly, the remote probability of Alpha Centauri having anything worth while visiting (such as a planet inhabited by kindly, beautiful, and wealthy sentient beings). The space travellers must then perforce venture to other stars in our galaxy, or even to other galaxies—with distances thousands and millions of times greater than those of our "neighboring" stars. It appears then that even at the velocity of light the further regions of our own galaxy and beyond must forever remain outside of the future pioneer's reach unless he is willing to set up a closed cycle within a vehicle, leaving the pleasure of discovery to his progenitors and contenting himself only with the pleasure of begetting the progenitors.

However, nothing daunted, the dyed-in-the-teflon enthusiasts point to some of the theories developed by some of the great theoretical physicists of the early 1900's: Lorentz, Fitzgerald, Minkowski, and others. These men established new theories of space, time, and motion, which later were molded into the special theory of relativity by the master, Einstein, who carried on where the others stopped. Einstein was good enough to anticipate the interstellar travel dilemma by publishing his restricted theory of relativity in 1905; one theorem in particular, "The Behaviour of Measuring Rods and Clocks in Motion," seems applicable. This postulate, based on the transformation equations developed by the Dutch physicist Lorentz transcends the classical laws of mechanics and dynamics derived by Galileo and Newton; instead, it embodies Einstein's equations of relativistic dynamics governing the motions of bodies at relative velocities up to that of light. This postulate describes two interesting effects:

1 The apparent length of a rigid body moving at a uniform velocity with respect to a fixed system is reduced in the direction of motion. This effect is known as the Fitzgerald contraction.

2 A moving "clock" will keep slower time than a stationary "clock," i.e., a clock fixed with respect to the moving "clock." Therefore time for an observer in a moving vehicle would pass more slowly than for an observer in a fixed system.

It is not the purpose here to derive or repeat the array of Lorentz transformations and the equations of relativistic dynamics which confirm these postulates. However the result can be stated very briefly:

The length of a rigid meter rod moving in the direction of its length with a velocity v, is $\sqrt{1 - (v^2/c^2)}$ of a meter, where c = velocity of light.

This rigid rod is then shorter when moving than when at rest and the greater its velocity is, the shorter is the rod. When $v = c$, then $\sqrt{1 - (v^2/c^2)} = 0$. For velocities greater than light the square root becomes imaginary. It can thus be concluded that relativistic dynamics define the velocity of light as a limiting velocity which can neither be reached nor exceeded by any material body.

Also, the second proposition—that a moving clock keeps slower time than a stationary clock—is derived from the Lorentz transformation.

If a fixed "observer" were to judge a one sec ticking clock moving at a velocity v, he would note that the time elapsed between two ticks of the clock is not one second, but $1/\sqrt{1 - (v^2/c^2)}$ sec, i.e., a somewhat longer time. Therefore the clock, as a consequence of its motion, goes more slowly than when at rest. In this case also, the velocity of light c is an unattainable limiting velocity.

This time change or "dilatation" has been brought forward by the interstellar travel proponents as a solution to the otherwise impossible time intervals required for such travel. In the *Journal of the British Interplanetary Society* (vol. II, July 1952, pp. 155–157), R. L. Shepherd of the BIS discusses the time dilatation effect with an experimental proof, an example, and a conclusion. He states:

". . . this effect [time dilatation] has been checked experimentally by observations on μ-mesons passing through the Earth's atmosphere. Cosmic ray primaries entering the atmosphere interact with the oxygen and nitrogen nuclei with the production of π-mesons which decay rapidly into μ-mesons. A typical μ-meson might have a kinetic energy of 3,000 Mev corresponding to a value of γ[1] equal to $1/30$ ($v = 0.9995c$). Now it is known that a μ-meson decays into an electron with the emission of gamma radiation and neutrinos. The mean life of a μ-meson at rest is 2.1×10^{-6} seconds; a μ-meson travelling at the velocity of light would traverse 600 metres in this time. The average height of formation of μ-mesons is 16 km., and if the mean distance traversed were only 600 metres, then only an immeasurably small proportion would reach the surface of our Earth. In point of fact a large proportion reach the surface, a fact which can only be explained on the basis of the time-dilatation effect."

He considers a numerical example of interstellar travel to the star Procyon (any other star could have been used of course) which is 10.4 light years distant. If a traveller left the earth for Procyon at a velocity 0.990 times that of light, then he would on return to earth have been aware of a time passage of only 3 yr, assuming no changes of velocity or stopping during his trip.

However, an observer at rest on the earth would have recorded a time interval of 21 yr. The traveller's clock or time perception would have been changed to one seventh that of the resting earthbound observer's. This value is derived from the afore-mentioned time dilatation factor of

$$\text{traveller's time} = \sqrt{1 - (v^2/c^2)} \times \text{Stationary time}$$

If the time dilatation effect is true then the time recorded by a moving observer should shrink in proportion to his

[1] [$\gamma = \sqrt{1 - (v^2/c^2)} = 1/30$]

approach to the speed of light.

Again, Shepherd recognized this hypothesis when he continued the above argument, by stating:

"If X [the traveller] could get close enough to the speed of light he could circumnavigate the universe in his lifetime, though he would find on returning that perhaps 10^{10} years had elapsed and the Solar System and stars that he knew had changed beyond recognition. This would in fact be one-way time travel."

Shepherd's paper did not remain unchallenged. In the Nov. 1952 issue of the *Journal of the British Interplanetary Society*, (vol. II, pp. 297–299) appear a letter to the editor by R. H. C. Newton rebutting the analysis, and a following rebuttal by Dr. Shepherd. Mr. Newton wrote:

"Part of Dr. L. Shepherd's analysis is unsound [because] it is implicit, in the derivation of the Lorentz formulae, that two observers, X in a rocket and Y on Earth, say, stand in symmetrical relationship to one another, i.e., that they are equivalent, and consequently there is no reason why X, during his unaccelerated flight, should not regard himself at rest and the earth bound Y as the traveller, in which case Dr. Shepherd's analysis, now applied to Y, will produce a contradiction. This is, of course, the famous 'clock-paradox' first published by Einstein in 1905.

"A simple resolution of this paradox is to be found in the paper by E. A. Milne and Y. J. Whitrow (*Phil. Mag.* XL, 1949, p. 1244)."

Mr. Newton, using the Milne and Withrow paper, then applied a rather lengthy algebraic argument to Shepherd's case. In summation, he stated that although X and Y will not agree on the precise landing and takeoff times (of X) they will agree on the duration of the round trip.

Shepherd replied that the clock paradox to which Newton drew attention "is no paradox at all," and that the arguments of Milne and Whitrow are based upon an assumption of symmetry between the "fixed" and "moving" observers. After stating that "this assumption is false," Shepherd continues with a somewhat more rigorous proof of his earlier description of the time dilatation and Fitzgerald contraction effects. His arguments are based on a paper by W. M. McCrea, University of California at Berkeley, which was published as a letter to *Nature* (London, vol. 167, April 28, 1951, p. 680).

McCrea's paper, in turn, received the earnest attention of Herbert Dingle, University of London, in an article on relativity and space travel in *Nature* (vol. 177, April 28, 1956, p. 782). Dingle had read a book by Sir George Thomson, "The Foreseeable Future" (Cambridge, 1955) which stated (p. 89) that the time contraction is real and space travellers of the future would experience this if they moved near the speed of light. Thomson had based his conclusion on the afore-mentioned paper in *Nature* by McCrea.

Dingle, during the past 30 years or so, has written various letters to *Nature*, rebutting occasional alleged errors in interpretations of Einstein's theory of relativity.

Apparently he did not notice McCrea's 1951 letter to *Nature*. At any rate, he has caught this in Sir George Thomson's book. Dingle's arguments are exacerbated by his references to the apparent lack of logic used by McCrea (and other modern physicists) and the imminence of high speed space travel.

It is not necessary to refer to Dingle's previous papers on relativity in order to review the one on space travel mentioned above. However, he has an obvious watch-dog attitude on interpretations of Einstein's postulates and he does not hesitate to bark and even nip a little when he sees an alleged error. He states in this *Nature* article:

"There could be no stronger confirmation of the misunderstanding to which I have referred than the fact that, fifty years after Einstein's clear and logical paper, this [time dilatation] can be called a matter of 'opinion.' It is still more serious that the 'best' opinion can be regarded as that which is simply a direct denial of the principle of relativity. The point to notice first is that the question is no longer an academic one; it has become a matter of profound social and philosophical importance, no matter whether space travel is imminent or not. It needs little imagination to see that if the public is led to believe that there is scientific sanction for the idea that it is possible to postpone the date of one's death by space travel, some very undesirable consequences might ensue. It is, therefore, necessary to bring the matter forward again, so that there shall no longer be differences of opinion on a matter of straightforward logic.

"After allowance has been made for the mental effort required to discard deeply rooted prejudices, it is impossible, after fifty years, to justify the wholesale abandonment of even elementary reasoning which physicists have allowed themselves to sanction. This outstanding triumph of reason over prejudice has been distorted into a triumph of magic over reason, and the state of mind thus engendered exposes us to dangers which it is impossible to exaggerate. I first directed attention to it nearly thirty years ago and have done so at intervals since; yet the mistaken interpretation of the Fitzgerald contraction and clock retardation persists.

"I know of no other example in the history of science in which such fantastic propositions have been put forward as sober scientific truth. The theory of relativity is unique, not merely in its difficulty, which is solely one of discarding prejudices and is excusable, but in its paralyzing effect upon the reason, which is not excusable. It looks as though the reaction from excessive rationalism that marked the beginning of the modern scientific era has gone too far, and that a course in traditional logic should be included in the training of all science students. Physicists should not have been misled by such words as 'contraction' and 'retardation' into supposing that the objects said to experience these effects suffer changes analogous to those produced by lowering temperature or by lengthening a pendulum. Sooner or later the lesson will have to be learned. Let us hope that it will be before some patriarch embarks on the trip to the Andromeda nebula in an attempt to outlive his great granddaughter."

Having thus warmed to his subject, Dingle fires his next round by paraphrasing Einstein's original paper (1).[2] He states Einstein's definition of the synchronism of clocks as follows:

"R (stationary) regards a clock at X as synchronized with his own when, if he sends a beam of light to that clock and receives it back, the time shown by the clock at X is half-way between the times, by his clock, of emission and return of the light. But this requires that M (moving towards X) will get a different result from the same process. Suppose M, at the time of R's emitting the light, is adjacent to R with his clock agreeing with R's.

"Then obviously M will receive the returning light earlier than R, and the time which it shows the clock at X to indicate will *not* be half-way between emission and return of the light by M's clock. Hence the clock at X will not be synchronized with M's. We cannot say that because R is at rest and M moving, R is right and M is wrong, for M might equally well retort that it is R who is moving. Hence our definition of synchronism, or of simultaneity, demands that two observers in relative motion will have different ideas of what events, occurring at different places, are simultaneous with one another.

We can now see what happens when our space traveller sets off. Nothing happens to his clock; but to compare it with a terrestrial one you must read them at the same time; otherwise you can get any result you like. The terrestrial observer, choosing what he calls the same moment, finds that the traveller's clock is slow. The traveller, however, says that the terrestrial observer has compared them at different moments; he makes the "right" choice and finds the terrestrial clock to be slow. Both are right—which would be impossible if the effect were something that happened to a clock instead of to a judgment of simultaneity. When the observers meet again, they are both at the same place and relatively at rest. Their judgments of simultaneity agree, and so their clocks agree. All this applies also to heartbeats. The observers will have "lived" the same time and made the same progress towards the tomb."

This, then, is Dingle's stand. It is unequivocal. He does not question McCrea's calculations. Indeed, he states that it would be misleading to do

[2] Numbers in parentheses indicate References at end of paper.

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so; the alleged error is not mathematical but lies rather in the "premathematical ideas."

In summary, Dingle's thesis in this paper is the proper definition of the simultaneity of two separated events experienced by two observers in relative motion. This motion is a relation between the observers and not something belonging to one or the other.

Professor McCrea answered Dingle in a letter in the same issue of Nature. He does not hide his convictions and begins with a clear statement:

"Prof. Dingle's exposition of relativity theory is wrong and a plain reply is needed."

McCrea's thesis is that the distinction between two observers (one moving and the other stationary) is an absolute distinction. He states:

"This is shown by the simple fact that one of the men has to use an engine and the other not. This common-sense distinction cannot, of course, be removed by any 'principle of relativity.' Even if the traveller chooses to regard himself as at rest and the Earth as departing and returning, it is still he and not the man on the Earth who has to use the engine. Therefore, no mere appeal to the principle of relativity enables us to say whether or not the two men agree as to the duration of the journey."

"The question is not, what has 'happened' to their clocks, but—what have their clocks measured? The answer given by the theory of relativity is very simple. For what we have been calling a free path corresponds in relativity theory to a segment of the geodesic world-line. The world-line of the observer on the Earth is a geodesic; the world-line of the traveller is not a geodesic (though it can be made up of parts of four different geodesics). In the case of this kind of geodesic, the geodesic interval between two events is the longest interval between them (not the shortest as in some other cases). The interval or proper-time, in accordance with the theory of relativity, is what is measured by a clock having the same world-line. Therefore, the clock on the Earth records a longer time than the clock carried by the traveller.

"In my example of the clock paradox, observer R remains at rest in an inertial frame, that is, remains in a free path; observer M transfers from one inertial frame to another, that is, he transfers from one free path to another and these different free paths do not combine into a single free path. Once again, this is an absolute distinction between R and M."

McCrea concludes with:

". . . by reason of the many tests of the theory, most of us are convinced that the theory can be correctly applied to the phenomena here considered."

Another rebuttal letter by Dingle completes the trilogy on space travel and relativity in this issue of *Nature*. Dingle, like McCrea, begins with a clear, clean-cut statement:

"Prof. McCrea wanders widely from the point and I do not propose to follow him."

and

". . . his remarks about geodesics are a wide and needless generalization of the problem; he has said nothing in answer to the definite statements I made."

Two important points stand out in Dingle's short letter.

1 The "absolute" distinction between the stationary and moving observer, resulting from the use of an engine by the moving observer, is eliminated when the period of engine "cutoff" (no change of velocity) is considered. During the period of engine inactivity the moving observer is in a "free" path; and he now has no basis for a distinction between the stationary observer without an engine.

2 Dingle asks McCrea to explain the number of different solutions to the clock paradox and "how it is that it has been left for him [McCrea] to be the first to discover, after forty-six years, that there is no paradox at all."

Comments and Conclusions

1 Two eminent physicists, both teachers of astrophysics and mathematics, disagree about Einstein's clock paradox.

2 One of them, McCrea, in his book on relativity physics (2) introduced a purported experimental illustration of time dilatation, depending on the proper lifetime of a meson.

3 Professor Dingle's main argument is based on the definition of the synchronism of two clocks or observers and the impossibility of either observer (or clock) being capable of determining whether he is moving.

4 McCrea's discussions of geodesics and world lines are rejected by Dingle as needless generalizations.

The writer has not seen McCrea's arguments used in other treatments of the clock paradox.

5 In general, "popular" books on relativity assert that time dilatation exists; however, the clock paradox is admitted.

6 Tolman (3, p. 197), in a solution of the clock paradox, stated:

"Whether we consider A or B to be the clock which moves, we obtain the same expression for the relative readings of the two clocks, to the order of approximation that has been employed. The treatment of the problem without approximation would involve the full apparatus of the general theory of relativity."

7 Einstein's original paper generated the paradox but did not give a solution.

8 Eugene Sänger, the German physicist, who has been a proponent of photon rockets, among other things, has boldly stated on a number of occasions (4, 5) that time dilatation exists and has predicted travel "around the universe" in a few seconds. However, he has given no new proofs.

9 Direct experimental evidence may be required to solve the clock paradox. As stated earlier, Shepherd referred to meson decay as a possible illustration of time dilatation; this was first described in the book by McCrea.

The writer has discussed this with M. M. Shapiro, Nucleonics Head, Cosmic Ray Branch, Naval Research Laboratory, who is a nuclear physicist, and a specialist in cosmic ray research. He stated that the anomalous meson decay mentioned by McCrea is indeed a manifestation of time dilatation in meson processes. Dr. Shapiro was unwilling to extend this dilatation principle to space travel.

It is interesting to note that McCrea has not used this experimental "proof" in his arguments with Dingle.

10 The whole concept of time dilatation seems fantastic and contrary to common sense. The quantum theory and such manifestations of Einstein's theory as the increase in rest mass of a moving body once seemed magical enough; however, their demonstration was the result of an orderly process of physical methodology and little affected the lives of the common man.

A phenomenon as startling and subjective as time dilatation, with time an intimate dimension of human experience, would only with very great reluctance be accepted by physicists and other scientists, even if some proof were given, because of the natural disinclination of many scientists (who may after all be human) to mistrust even a valid measurement which is so contrary to common sense. The whole matter would be further complicated by the social disturbance created by slowly aging astronauts outliving their earth-based comrades.

References

1 *Annalen der Physik*, vol. 17, 1905, p. 891.

2 "McCrea, W. H., "Relativity Physics," Methuen & Co. Ltd., London, 1947, p. 83.

3 Tolman, R. C., "Relativity, Thermodynamics and Cosmology," Oxford, 1934.

4 Sänger, Eugene, "Photon Rockets," *Aero Digest*, vol. 73, July 1956, pp. 68–70.

5 Verbal presentation at the IAF Congress, Rome, Italy, Sept. 17, 1956.

6 Leiber, L., and Leiber, H., "The Einstein Theory of Relativity," Rinehart, New York.

Jet Propulsion News

Alfred J. Zaehringer, American Rocket Company, *Associate Editor*

ROCKAIRE: For extreme flexibility and mobility, an airborne launching platform

Future Sounding Rockets

Aerojet-General group describes four new high altitude rocket systems. Details of other new sounding rockets also disclosed.

WHAT happens when a high altitude rocket exhausts its altitude potential and funds for development of new rocket systems are limited? Answer: Take components and techniques from liberally subsidized weapons programs and combine them into new sounding rocket systems.

This is essentially the conclusion reached by six Aerojet-General men[1] in a paper prepared for presentation at the Annual Meeting of the AMERICAN ROCKET SOCIETY last month.

Principles Applied: By way of example, the Aerojet group detailed four advanced sounding rocket systems based on this concept:

• Rockaire complex. Designed to achieve almost the ultimate in launching mobility, this system uses an airplane as a launching platform. The plane zooms into a vertical attitude, fires the sounding rocket upward.

Designated Aerosound (see picture), the sounding rocket part of Aerojet's planned Rockaire system would be powered by the firm's 1.8 KS 7800 engine. A simple cone-cylinder fairing would cover the payload and contour smoothly into the motor case. Four tail fins would provide necessary static stability, join into a cylindrical fairing covering the rocket nozzle.

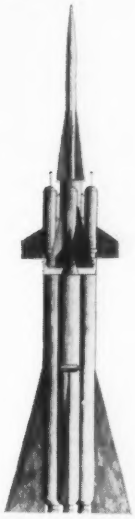
Launched at Mach 0.8 at 35,000 ft, the Aerosound, say Aerojet planners, would carry a 40-lb payload to a summit altitude of 45 miles, a 20-lb payload to 54 miles. Two 1.8 KS 7800 engines mounted in tandem and fired sequentially would push a 40-lb payload to 110 miles.

A Rockaire system using a solid propellant rocket is reported to be under development at Douglas Aircraft and almost ready for launching.

• Multiple unit system. Using available solid propellant rockets, says the Aerojet group, scientists can assemble staged vehicles yielding almost any desired performance. Gross take-off weight may be relatively high, but unit costs are strikingly low.

One such system, planned by the group, would be a boosted, two-stage vehicle with a total initial weight of 12,426 lb (see drawing). It would carry a free-coasting, 6.5-in.-diameter, 250-lb payload to an altitude of 90 miles. Provision is made for the addition of a 200-lb, third-stage rocket—in which case payload would be cut to 50 lb, but altitude would be extended to 490 miles.

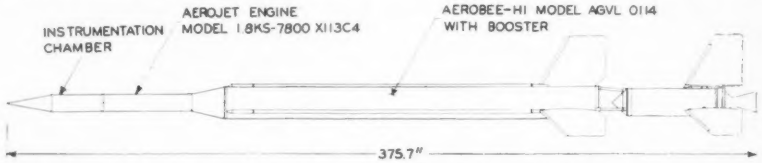
Booster would be four 5ONS-4500 rockets; the first stage would consist of four 5KS-4500 boosters; and the second stage would be a 2KS-36250 unit. The third stage rocket, if used, would be a 4KS-8000.



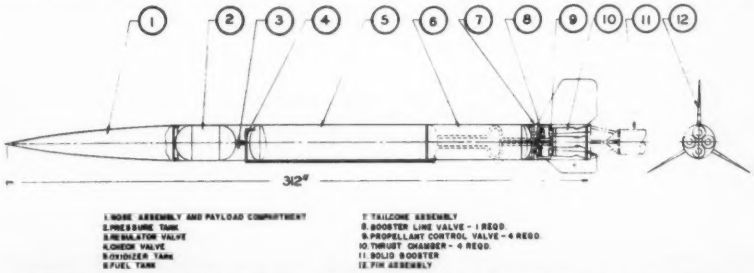
MULTI-ROCKET SYSTEM: High gross take-off weight but strikingly low unit costs

• Spaerobee system. This is visualized as a simple two-stage vehicle with booster (see sketch) that could transport a 20-to-60-lb payload to an altitude of approximately 400 miles.

The first stage would be an Aerobee Model AGVL 0114 with its booster. The nose section would be removed and the short duration 1.8KS-7800 solid engine added as the second stage. A nose cone and cylindrical section attached to the second stage would house the payload; and a flared skirt



SPAEROBEE: For a 400-mile summit altitude capability, a second stage to the Aerobee


1 2 3 4 5 6 7 8 9 10 11 12
312"
1. NOSE ASSEMBLY AND PAYLOAD COMPARTMENT
2. PRESSURE TANK
3. REGULATOR VALVE
4. IGNITION VALVE
5. OXIDIZER TANK
6. FUEL TANK
7. TAILCONE ASSEMBLY
8. BOOSTER LINE VALVE - 1 REQD.
9. PROPELLANT CONTROL VALVE - 4 REQD.
10. THRUST CHAMBER - 4 REQD.
11. SOLID BOOSTER
12. FIN ASSEMBLY

FOUR-CHAMBERED ROCKET: Three more thrust chambers and 50 miles higher

[1] W. C. House, C. H. Dodge, R. D. Waldo, A. Schaff, Jr., J. L. Fuller, and O. J. Demuth.

would be used to give the second stage its stability.

• Four-chambered system. An advanced vehicle similar to the Aerobee, this system would use four thrust chambers, fired in pairs, to extend the 250-mile summit altitude (the limit presently indicated for Aerobee-type vehicles) beyond 300 miles. It would carry a 100-lb payload.

The vehicle (see sketch) would employ a 2.0 KS 36250 booster as well as pressurized propellant servicing. An inert-gas-pressurized propellant feed system similar to the Aerobee system would be used to feed the thrust chambers. Using inhibited red fuming nitric acid and aniline base fuel, each chamber would produce 2600-lb thrust.

Pressure regulators, valves, and ceramic-lined thrust chambers would be taken from a propulsion system now in production. The resultant vehicle would have a body diameter of 18 in.; but launching towers at White Sands, Holloman or Fort Churchill, with minor modifications, could easily accommodate the vehicle.

Briefly Noted

In other papers prepared for the two high altitude sounding rocket sessions at the ARS Annual Meeting:

✦ Homer E. Newell, Jr., Naval Research Laboratory, reported that a number of new sounding rockets are under development. And solid propellant vehicles comparable in altitude and payload capabilities to the liquid propellant Aerobee-Hi may be available in the near future.

Dr. Newell also revealed that preparations for Aerobee firings at Fort Churchill cost many millions of dollars. The $30,000–$40,000 it costs (including price of the rocket itself) for each Aerobee firing, he noted, is too great for most private institutions. The hope for these groups lies in the development of less expensive solid propellant sounding rockets comparable to the Aerobee, such as the Iris (U. S.) or Skylark (British), or in somewhat smaller solid propellant rockets, such as the French Monica.

✦ Actual details of the British Skylark were disclosed in a paper by E. B. Dorling of the Royal Aircraft Establishment. The unguided vehicle, scheduled for test firings by the end of 1956, is 25 ft long, 17½ in. in diameter and will carry a 65-lb payload. Powered by the Raven solid propellant motor, the rocket is expected to reach an altitude of 490,000 ft. Addition of a booster may extend altitude capability to 700,000 ft.

✦ E. Vassy, University of Paris, reported that several improvements have been made in the French Veronique. Consequently, it is expected that the rocket will exceed previous performances in which it reached a top altitude of 135 kilometers.

The smaller, three-stage powder rocket ATEF, which has reached an altitude of 80 kilometers, is also expected to improve its performance as a result of new developments.

✦ Two new versions of the Aerobee-Hi, expressly designed for upper air research in the forthcoming IGY program, were described by John W. Townsend, Jr., of the Naval Research Laboratory and Robert M. Slavin of the Air Force Cambridge Research Center.

One version, designated the Air Force Aerobee-Hi, is designed to carry a 150-lb payload to an altitude of 140 miles, assuming launch at sea level and an Arctic atmosphere. The other version, Navy Aerobee-Hi, is designed to reach 147 miles under the same conditions.

Use of a ceramic-lined thrust chamber (still under development) in place of the regeneratively-cooled chamber now in both versions is expected to raise the previously mentioned summit altitudes by 10 miles. And a change in the fuel tanks of the Navy Aerobee-Hi will add another 10 miles to its altitude capability.

The Navy model then will be capable of carrying a 150-lb payload to 167 miles; the Air Force model, to 150 miles. (Sea level launch at White Sands would add another 15 miles altitude capability, while a 30-lb reduction in payload would afford a 17-mile increase in altitude.)

✦ Far from the inexpensive solid propellant sounding rocket sought by private research groups, the recently developed Nike-Cajun, nevertheless, represents a significant step in the right direction. Cost of the vehicle—including scientific instruments and booster—is about $7700. This is on an "assemble-it-yourself" basis, does not cover handling and launching of the 1500-lb vehicle which requires a modified Nike launcher. However, as pointed out by the four authors (Leslie M. Jones and Nelson Spencer, University of Michigan; William Stroud, Fort Monmouth Evans Signal Laboratory; Warren Berning, Aberdeen Ballistic Research Laboratory) of the Nike-Cajun paper, the work with solid propellant sounding rockets is just starting. They reported that interesting developments with slow burners, truly small rockets, and very high altitude rockets are under way and will be completed soon.

(Other papers and happenings at the ARS Annual Meeting will be covered in an upcoming issue of JET PROPULSION.)

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A Look at England's Missile Program

LEONARD BERTIN

Heavy security regulations combined with a general policy of not committing industry to production of any weapon until the political and military situation absolutely requires it has opened Britain to charges that it is doing "practically nothing" in the way of missile development.

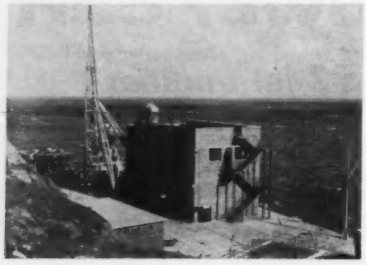
Leonard Bertin, science correspondent of London's The Daily Telegraph and Morning Post, refutes these charges. He has toured the major missile facilities on the British Isles and traveled to his country's long-range weapons establishment in Woomera, Australia. This is his report:

WITH the limited resources it has available, England's missile development program is actually achieving a great deal.

At the Royal Aircraft Establishment, for example, scientists are constantly exploring new concepts, delving into basic missile research. And the Farnborough facility, well equipped with instruments such as the TRIDAC guided missile simulator, is the center of aerodynamic research and computations not for weapons system alone but also for related projects.

As witness: Among the projects now underway at the Establishment is the development — in conjunction with various British universities—of a new high altitude research rocket, the Skylark. Tentatively scheduled for firings at Woomera by the end of the month, this unguided rocket is expected to reach an altitude of 700,000 feet eventually.

The Skylark project, of course, represents only a small part of the work undertaken at Farnborough. Nor is the Royal Aircraft Establishment there the only British missile facility figuring in the news.



To deck hands, "H.M.S. Rock-'n-Roll"

Hawker Siddeley, for instance, recently set up a new missiles research and development center near Coventry. And at the Ministry of Supply's Westcott, Bucks, rocket propulsion establishment, where there are many testbeds already in operation, there is a testbed under construction that is designed for motors up to 200,000-lb thrust.

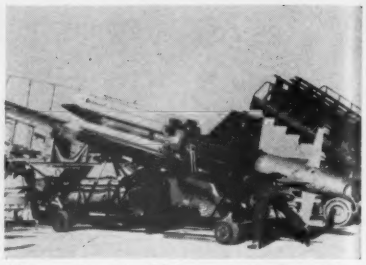
In the way of firing ranges, the Ministry of Defence is building a new one at South Uist, off the west coast of Scotland. Scheduled for completion in 1958, the range will be capable of handling large missiles.

Cliff Dwelling: Until the South Uist range is completed, however, the Aberporth establishment on the Welsh coast remains the only range in Britain where large missiles may be fired. Perched on 450-ft cliffs above Cardigan Bay, the Aberporth site occupies about 250 acres and has a clear run of 70,000 yd heavily dotted with tracking stations.

Work at Aberporth goes on at a fast pace and under high pressure. In addition to target drones (chiefly Firefly U-8's) and other small vehicles constantly buzzing over the area, about 1000 large test missiles are launched there every year.

In a recent demonstration of the establishment's normal program of activities, Aberporth scientists launched three major test missiles. All the test vehicles were designed for electronic guidance systems but, on this occasion, were apparently operating without guidance.

The first missile fired—not counting the 5-in. sighter rockets which left the ground every 20 minutes for the benefit of electronics men setting up new equipment—was an Armstrong-Whitworth rocket with four wrap-around boosters but sans sustaining motor. It was clearly related to the surface-to-air (and probably also surface-to-surface) weapon that the company is developing for the navy. It was fired from



Aberporth test vehicle ready for launching

the center ramp of a triple launcher "on board" a 700-ton floating device known as the Clausen Rolling Platform (CRP). Without its sustainer motor, the missile followed a steeply curving trajectory under the influence of gravity.

The CRP, built in a land-locked basin at the foot of the cliffs, carries all equipment needed to pick up and track targets, compute interception trajectories, fire and guide missiles, and monitor telemetered signals. Very similar to the platform installed in the 8600-ton Girdleness missile development vessel (now out on trial runs), CRP has launchers and radars independently stabilized to maintain alignment however the ship moves.

The second missile launched was a Bristol Aircraft ramjet boosted to supersonic speeds by four wrap-arounds. The vehicle's two ramjets were set on short stub wings.

An English-Electric missile, also with four wrap-around boosters, was the last one to be launched. This vehicle, with little doubt, represented an advanced stage in the development of an antiaircraft weapons system. English Electric is also working on the development of a new ramjet missile.

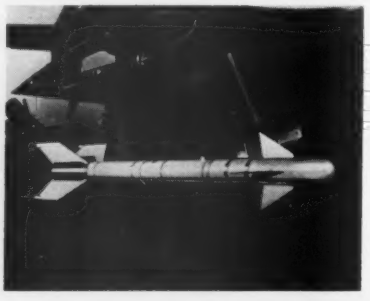
Self-Defense: Authorities in England are not ignoring the matter of intercontinental missiles. Too, they are plugging for the replacement of old naval vessels by new guided missile cruisers. But a major concern of the British, naturally, is defense. And, in the opinion of many, guided missiles are destined to play a vital role in this defense. Thus, they believe, this is where the emphasis should lie in England's missile development program.

MISSILES

• The Air Force recently announced in Detroit that it has a nuclear-armed, heat-seeking missile under development. Reference was probably to Douglas' liquid rocket Ding-Dong.

• Production of launching equipment for Terrier air-to-air missile is said to be underway on a $23 million contract awarded to Northern Ordnance of Minneapolis.

• Navy's XAAM-N-7 Sidewinder (see photo) is now operational on carrier-based planes in the Far East and in the Mediterranean. The air-to-air guided missile, produced by Philco, is powered by a double-base solid propellant rocket. It is about 9 ft long, has a diameter of about 6 in., and weighs about 100 lb. The Sidewinder reportedly is equipped with an active heat-seeking guidance system, and is said to have a high single-shot kill probability.



• Another Air Force bird, Falcon, is now standard armament on the F-89H jet interceptor (see photo). Each wingtip pod has been modified to carry three Falcon's plus 21 Mighty Mouse rockets.

• The Defense Department has released long overdue information on the Army Redstone. Described as a prototype for the Jupiter IRBM, the Redstone is about 69 ft long and 70 in. in diameter. It is powered by a North American LOX-alcohol rocket engine having turbopumps operated by hydrogen peroxide. Engine thrust rating is pegged between 65,000 and 75,000 lb. Like Jupiter, Redstone is produced by Chrysler Corp., with Ford Instrument furnishing guidance and Reynolds Metals Co. the aluminum hardware.

• Late in September, first firing of Jupiter mock-up was reported at AFMTC range in Florida. The firing, sans guidance, was intended to check out powerplants and study re-entry effects. Unconfirmed reports state that the firing used a three-stage vehicle. First stage was made from a Redstone unit which dropped off some 200 miles from Cocoa. Second stage consisted of a bank of four Baby Sergeant solid propellant rockets which landed some 800 miles downrange. Last stage was one Baby Sergeant which reached a peak altitude of 600 miles and a range of 3000 miles.

• Continued support of intercontinental cruise missile program was assured when Air Force granted a $65 million contract to North American on the XSSM-64 Navaho missile.

• General Electric has received a multimillion dollar contract for development and production of arming and fuzing systems for guided missiles. The program, part of a prime contract with Army Ordnance, Picatinny Arsenal Atomic Applications Lab, will be carried out at GE's Missile & Ordnance Systems Dept. in Philadelphia.

Under another government contract, GE will build unique shock tunnels and ballistic firing ranges to simulate conditions of nose cones re-entering the atmosphere in a nose cone research and development study for the Air Force.

• Bell Aircraft recently revealed that it was now a major supplier of Nike sustainer rocket motors. The uncooled motor, lined with Niafrax A, is about $18^1/_2$ in. long, has a diameter of $6^1/_2$ in., and weighs 20 lb. Thrust rating is

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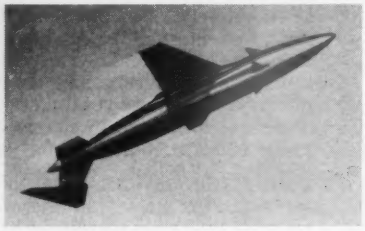
2600 lb at 10,000 ft for 35 sec. Red fuming nitric acid and jet fuel burning at 330 psia produce a temperature of 5000 F. Nozzle erosion and manufacturing control of ceramics were major problems which were solved.

• An NACA development, the Nike-Cajun two-stage solid propellant rocket, will carry a 40-lb nose cone to an altitude of 100 miles with a speed of about Mach 6. Over 100 of these rockets will be fired during IGY.

• General Electric reveals that its first-stage Vangurd rocket will deliver over 27,000-lb thrust. Called the X405, it has a burning time of about 150 sec. The motor will burn hydrocarbon fuel and liquid oxygen at high chamber pressure. Motor will be turbopump-fed and gimbal-mounted to change thrust direction by as much as 5 deg.



• What appears to be the first rocket powered drone was announced by Radioplane Co. (Van Nuys, Calif.). Designated RP-70 (see photo), the target craft is in the Mach 0.9 class at 50,000 ft. It is powered by a solid propellant rocket motor and has a flight endurance of 8–10 min. The airframe weighs 300 lb and is over 9 ft long with a span of 5 ft. A steel rocket motor case makes up the mid-fuselage section. All other structures are of glass fiber reinforced plastic. The craft is now ready for flight tests.

• Iris is a new research rocket that is slated to carry 100 lb of instruments to an altitude of 200 miles. Atlantic Research is to develop the single-stage solid propellant rocket for the Navy. Ready date is 1958. Iris' dimensions: 13 ft long, 12 in. diam.

• Arcon, another single-stage solid rocket by Atlantic Research, is being developed for Naval Research Lab. The 6-in.-diam, 12-ft-long Arcon is designed to hit an altitude of 60–70 miles.

• Little John is a scaled-down version of Honest John. The baby rocket has a diam of $12\frac{1}{2}$ in. and is some 12 ft long. It is used as a test and training vehicle.

• Martin now figures that about 12 Vanguard launchings will be needed to establish one good orbit. Big task now, according to Martin, is to ready test facilities at Cocoa.

• Space mice? Contribution of the Animal Trap Co. (Lititz, Pa.) to the Vanguard program will be a mousetrap spring to close access hatches on the satellite vehicle.

• A more conventional Vanguard component will be the hermetic integrating gyro HIG-6 unit being built by Minneapolis-Honeywell. Weighing about 4.6 lb, it is enclosed in a cylindrical container 5.9 in. long, and 3.07 in. diam. Principal parts are gyro wheel, gimbal, signal pick-off, and torque generator. Transistorized temperature controllers will also be used. HIG's job will be to keep the rocket on course and to gradually tip the rocket's trajectory parallel to the earth.

• Aerojet General Corp. recently broke ground in Sacremento (Calif.) for a new $13 million plant in which the company will produce large rocket engines for Air Force missiles.

AIRCRAFT

• A new rocket plane, designated the X-15, is under development at North American Aviation, Inc. The craft, it is reported, will be entirely of steel and capable of speeds in excess of 4000 mph at altitudes above 38 miles.

Meanwhile, the speed and altitude research work carried out with the rocket-powered Bell X-2 which crashed recently (JET PROPULSION, Nov., p. 992) is continuing at Edwards AFB. The Bell X-1B and X-1E are reported to have taken over—as a team—the functions of the X-2. Use of rocket nozzle extensions is expected to boost high altitude performance of X-1E.

Before the X-2 crashed, indications are that it reached a speed above 2100 mph. Although the plane had a design speed of 2500 mph, the best previous run was around 1900 mph. The X-2 was valued at $3 million.

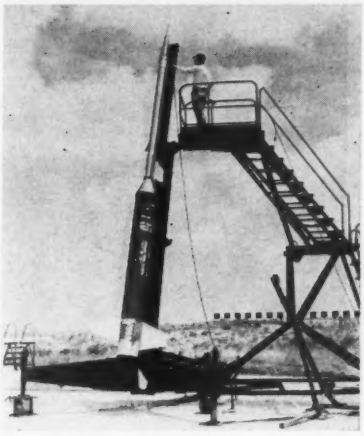
• Convair's delta-wing B-58 Hustler, first U. S. supersonic bomber, is now entering the flight test phase. Powered by four General Electric J-79 turbojet engines, the B-58 is designed for supersonic speeds and altitudes above 50,000 ft. About 95 ft long and 30 ft high, the Hustler has a wing span of approximately 55 ft with elevons in the trailing edge of the triangular wing.

• In a recent speech, Boeing Airplane Co.'s Director of Finance, Paul S. Ford, predicted that another 100 to 150 large jet airplanes will be sold to commercial airlines for delivery within the next five or six years.

• Boeing Airplane Co. has ended production of the B-47 Stratojet. The last bomber, a B-47E (see photo), was delivered to the Air Force on Oct. 24.

Wallops Island Stepping Stone to the ICBM

IN TEST flight off Virginia coast, four-stage NACA research rocket exceeds 5000 mph, pushes beyond 189-mile altitude.



NIKE-CAJUN No. 1: From Wallops Island a valuable contribution to the IGY

ONE of the busiest participants in this country's missile research program, the National Advisory Committee for Aeronautics, recently slowed down long enough to let the public look at some activities of its Pilotless Aircraft Research Station at Wallops Island off the Virginia coast.

Here, NACA scientists are actively engaged in the collection of basic aerodynamic data concerned with such factors as control, balance, aerodynamic heating, etc. With this data, NACA scientists hope to bridge the gap between theory and actuality in missile development.

ICBM Design: One of the top-priority programs now underway at Wallops Island is devoted to gathering hypersonic research data, much of which is expected to aid materially in the development of intercontinental ballistic missiles.

To collect this data, NACA scientists have developed and are using mostly three- or four-stage solid propellant rocket combinations that attain tremendous altitudes and speeds (see picture above).

Two years ago, for example, a four-stage solid propellant rocket combination fired by NACA scientists reached a speed of Mach 10.4 and a peak altitude near 200 miles. The test round used standard Nike boosters for the first two stages, a Thiokol T-40 booster for the third stage, and a Thiokol T-55 booster for the fourth stage. Over-all length was 35¾ ft and gross weight was 2800 lb.

Somewhat similar to this early pacesetter, the latest four-stage rocket combination to be used in the Wallops Island hypersonic research program has a blunt ogival nose (which, it is believed, will be a design characteristic of ICBM vehicles), a finless, flared tail, and uses an Honest John rocket in place of the first-stage Nike.

Side Effects: In one investigation, scientists of the Pilotless Aircraft Research Station combined a Nike booster with a Deacon rocket to obtain research data on missiles at high Mach numbers and medium altitudes. In conjunction with work by a University of Michigan group, this led to the development of a high altitude version of the Nike-Deacon which was first fired from Wallops Island.

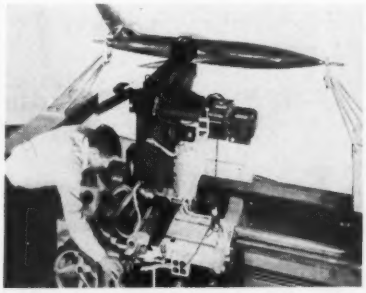
Continuation of this cooperative effort resulted recently in the development of a new high altitude sounding rocket, the Nike-Cajun (see picture). The Cajun rocket, specified by NACA, is basically a Deacon with a modern propellant. First fired from Wallops Island last July, Nike-Cajuns will join Aerobee sounding rockets in exploring the upper atmosphere and will play an important role in the upcoming IGY research program.

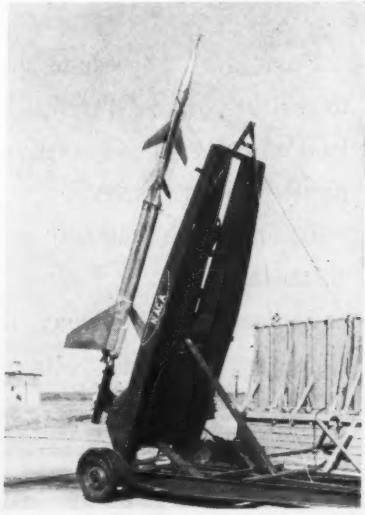
Pre-flight Program: Other research projects undertaken at the Pilotless Aircraft Station are devoted to the design development of future supersonic aircraft. To determine such characteristics as lift, stability, drag, etc., of future fighters, NACA scientists fit booster rockets to a small, "general research model of a typical supersonic airplane," fire the model out over the Atlantic.

Wallops Island firings, of course, are only one phase of NACA research. Before and after test model launchings, a great deal of time is spent on research in the various NACA laboratories throughout the country, especially at Langley Aeronautical Laboratory which operates the Wallops Island Station.

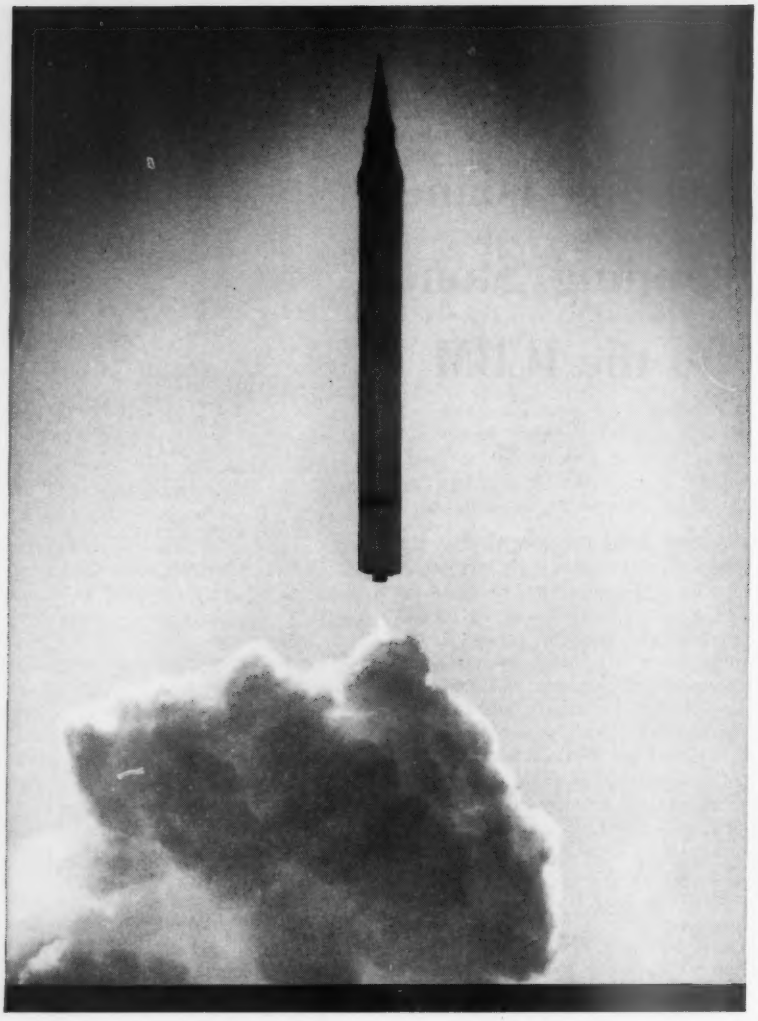
At Langley, the supersonic models are checked to insure dimensional accuracy and perfect balance before they take to the air over Wallops Island. Specially built equipment such as the profile machine (see picture) carefully measure wing contour and thickness, check tail surfaces at key points, etc. Later, NACA scientists load the models with instrumentation, move them on to the Island for actual flight tests.

This, of course, is but a quick look at a small part of the work carried on by NACA at its Wallops Island Research Station. But it underscores the vital role being played by the Pilotless Aircraft Research Station in this country's aircraft and guided missile program.





PRECISION CHECKOUT: Research models must be extremely accurate dimensionally and perfectly balanced before they are ready for launching.



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GOVERNMENT

• A new training center for experimental aerodynamics to serve the NATO countries will be located at Rhode St. Genese, near Brussels, Belgium. The center offers a two-year postgraduate course in the aeronautical field for 8 NATO nations.

• Navy's Distinguished Civilian Service Award has been awarded to Constantine L. Zakharchenko for development work on the Petrel guided missile. Patrol aircraft squadrons in both the Atlantic and Pacific Fleets are now being armed with the air-to-surface missile.

• Army interest in VTOL and STOL vehicles has prompted award of design study contracts leading to the development of a 250-hp gas turbine aircraft engine. Contracts were issued to: Continental, Lycoming, Studebaker-Packard, and Curtiss-Wright.

• United States Civil Service Commission (Washington, D. C.) is now accepting applications for engineering and physical science positions at the Potomac River Naval Command and at the Fort Belvoir Army Engineer Center.

• United States Atomic Energy Commission (Washington, D. C.) has established a program of special fellowships to encourage more students to study the physical sciences and nuclear engineering.

COMPANIES

• Powerplants for future aircraft and missiles will be designed in a new General Electric Co. facility at Danville, Calif. The new facility will be under the direction of the Flight Propulsion Laboratory in Cincinnati.

• Another missile facility in the San Francisco Bay area was announced by Lockheed's Missile System Division. A third laboratory building is to be constructed on the division's 22-acre center in Stanford University's industrial park. Lockheed's total area there now approaches 1 million sq ft.

Lockheed's 1956 missile sales are expected to be $50 million. But of the major and minor missile projects underway, only two have been announced: the Air Force X-7 ramjet test vehicle and a hypersonic ballistic rocket used in ICBM re-entry research.

• Douglas Aircraft is getting more space for its missile activities by leasing 61,000 sq ft in West Los Angeles. The new location, designated A-15, is part of the Santa Monica Missile Division.

• Northrup Aircraft, too, is expanding its guided missile program by leasing an additional 72,000 sq ft administration facility in Torrance, Calif. Meanwhile, Northrup is considering a merger with Vertol Aircraft of Morton, Pa., a large helicopter manufacturer.

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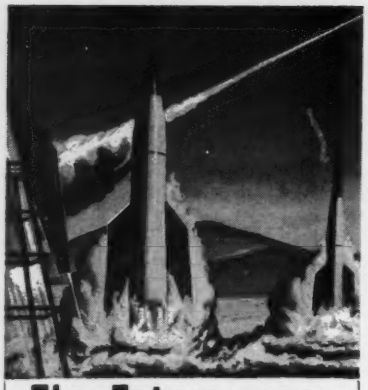

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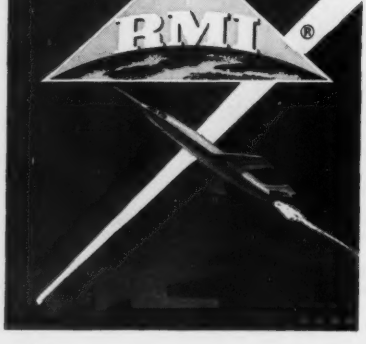


• J. B. Rea (Santa Monica) will supply a computer for Edwards AFB Ballistic Test Facility and analog-to-digital converters for Edwards and for the Naval Air Missile Test Center at Point Mugu, Calif.

• Pacific Automation Products, Glendale, Calif., has contracts of $4.1 million for design, manufacture, and installation of guided missile control and instrumentation cabling systems with General Dynamics Corp.

• Testing of fuel systems and auxiliary power systems for rockets and missiles will take place at Thompson Product's new $10 million Accessories Division on a 1000-acre site near Roanoke, Va. The project is scheduled for completion in 1961.

• U. S. Bureau of Aeronautics has awarded Raytheon Mfg. Co. a contract for more than $60 million to produce air-to-air guided missiles for Naval Aviation. The company maintains missile facilities at Bedford, Lowell, Maynard and Andover, Mass., and at Point Mugu, Calif., and White Sands Proving Ground, N. Mex.

INSTITUTIONS

• Two projects currently underway at University of Detroit's Missile & Rocket Section are thermochemistry of solid fuel ramjet propellants and work on a new type of aerial delivery system.

• Ninth Annual College-Industry Conference, sponsored by American Society for Engineering Education, will be held Jan. 30–31, 1957, at the Univeristy of California, Los Angeles. Theme: "Improvement of the Engineer—A Dual Responsibility of Industry and the Engineering School."

• National Science Foundation will award three grants totaling $89,910 to provide for an expanded program of translation of Soviet scientific publications, establishment of a center to collect scientific translations from all languages, and procurement of rare chemical publications from many different countries.

• In a move to step up the supply of engineering graduates for the aviation industry, Northrop Aeronautical Institute (Inglewood, Calif.) has begun construction of a new $200,000 engineering education building (see artist's sketch).

• National Science Foundation (Washington, D. C.) is now accepting applications for a new program of Science Faculty fellowship awards. The fellowships are offered as a means of improving the teaching of science, mathematics, and engineering in American colleges and universities, are open to any U. S. citizen "who holds a baccalaureate degree or its equivalent, has demonstrated ability and special aptitude for science teaching and advanced training, has taught at the collegiate level as a full-time faculty member for not less than three years, and intends to continue teaching."

• University of California has received a $1-million grant from General Dynamics Corp. to assist in expansion of the University's La Jolla campus to provide for a graduate program in science and technology.

• The Martin Co. will award prizes and awards totaling $24,000 for essays on any aspect of design, manufacture, or use of orbital vehicles. Seniors and graduate students majoring in engineering or science are eligible to enter. All essays are due at the contestant's school on or before March 1, 1957.

• Northwestern University, is sponsoring a Gas Dynamics Colloquim which is to run from October 1956 to May 1957. The technical lectures will be free to professional scientists and engineers and to students. Of particular rocket interest are: "Combustion Experiments in Rocket Motors" on Jan. 17, 1957, and "The Use of Ozone as a Rocket Propellant" on Feb. 14, 1957.

FOREIGN

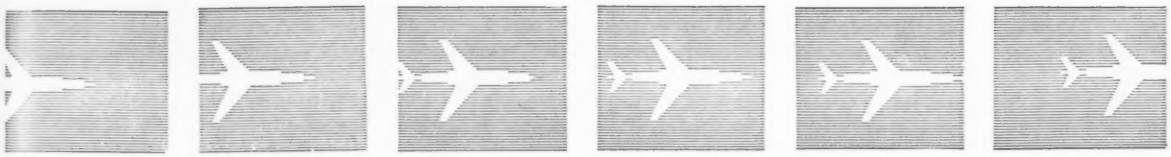
Russia: According to latest Soviet news sources, launching the Red satellite will take place in 1957. A Moscow news article written by leading physicist Georgi Pokravsky states that an aluminum sphere 20–24 in. in diameter, weighing about 100 lb will be placed in an orbit by a huge three-stage rocket.

France: Quest-Aviation (formerly S.N.C.A.S.O.) has announced that it will have a new long-range surface-to-air missile ready for launching shortly.

England: British government has approved British Overseas Airways Corp.'s request for purchase of 15 Boeing 707 jet airliners to be powered by Rolls-Royce Conway engines.

• Royal Navy has placed an order for new de Havilland 110 twin-jet fighters (see picture). Craft will be armed with guided missiles.

ENGINEERS · SCIENTISTS



RECENT BREAKTHROUGHS IN SUPERSONIC AND HYPERSONIC KNOWLEDGE AND TECHNOLOGY— BASIS OF MAJOR RESEARCH AND DEVELOPMENT ACCELERATION AT REPUBLIC AVIATION

Alexander Kartveli, Vice President in Charge of Research and Development, Invites the Inquiries of High Calibre Engineers and Scientists

Recent discoveries justify a large scale, long range integrated attack on all the complex, interrelated aspects of passage through the upper atmosphere, in the opinion of Alexander Kartveli, creator of Republic's famous family of Thunder-Craft.*

Republic's R & D activities are now being materially augmented and accelerated to speed the exploration of this new knowledge and technology. The broad areas under study are:

- **Hypersonic and Satellite Weapons Systems.**
- **Advanced Propulsion Systems.**
- **Nuclear Energy Applications to Aircraft.**
- **Capabilities of Materials in Hypersonic and Nuclear Environments.**
- **Electronic systems development to exploit the full potential of the most radical concepts of flight.**

The quality of the opportunities for creatively unhampered professional men with specialized experience in many fields is evident. Republic welcomes your inquiries regarding positions in any one of the areas outlined:

Positions Open At All Levels

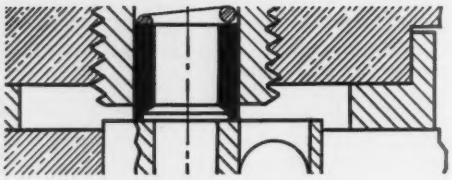
NUCLEONICS
ELECTRONICS
SERVOMECHANISMS
PROPULSION
STRUCTURES
FLUTTER & VIBRATION
DYNAMICS
AERODYNAMICS
THERMODYNAMICS
FIRE CONTROL SYSTEMS
FLIGHT CONTROL SYSTEMS
INERTIAL NAVIGATION
INFRA-RED
OPERATIONAL ANALYSIS OF WEAPONS SYSTEMS
AIRFRAME AND SYSTEMS DESIGN
MATERIALS

*Each Thunder-Craft in turn has represented a significant advance in aircraft design. Latest member of this famous family is the incredible F-105 Thunderchief, most advanced USAF fighter-bomber—supersonic and nuclear-weapons carrying.

Please address complete resume of your technical background to: Engineering Personnel Manager Mr. David G. Reid

REPUBLIC AVIATION

FARMINGDALE, LONG ISLAND, NEW YORK



MECHANICAL ENGINEERS

Continually expanding programs at Northrop Aircraft are creating new opportunities for mechanical engineers in the following areas: launching and landing gear design, hydraulics and pneumatics, control systems, and equipment.

You'll enjoy the fine spirit of cooperation at Northrop. The new multi-million-dollar engineering and science center, now nearing completion, will be a great place to work in, both as to its modern architectural design and newest scientific installations. You'll be associated with a top engineering team on such notable projects as Northrop's new supersonic trainer airplane, Snark SM-62 intercontinental missile, and other advanced aircraft and missile programs.

You'll be given constantly fresh, challenging assignments. Remuneration will be substantial, with many benefits that are unexcelled in the entire industry—health and life insurance, college educational reimbursement plan, regular vacations plus extra year-end vacations with pay, and a generous retirement plan.

At Northrop, the progress of personnel is important. Initiative and ability are recognized and encouraged, and full opportunity is given to present and discuss ideas.

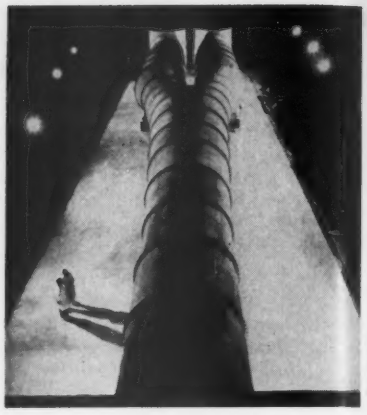
You will find the career opportunity you are seeking at Northrop, pioneer in the design and production of all weather and pilotless aircraft. If you qualify for one of these attractive positions, contact the Manager of Engineering Industrial Relations, Northrop Aircraft, Inc., ORegon 8-9111, Extension 1893, or write to: 1015 East Broadway, Department 4600- K, Hawthorne, California.

NORTHROP

NORTHROP AIRCRAFT, INC., HAWTHORNE, CALIFORNIA

Producers of Scorpion F-89 Interceptors and Snark SM-62 Intercontinental Missiles

5-A-86



• De Havilland has added a double-ended silencer to its jet engine testbed at Hatfield, Hertfordshire (see picture), claims the unit can handle engines of more than 30,000-lb thrust with only a low pitched rumble.

• The Short Brothers and Harland VTO jet is expected to be ready soon for flight testing.

• De Havilland is working on a new 120-seat jet airliner. Temporarily designated D.H. 118, it is figured to be ready by 1962.

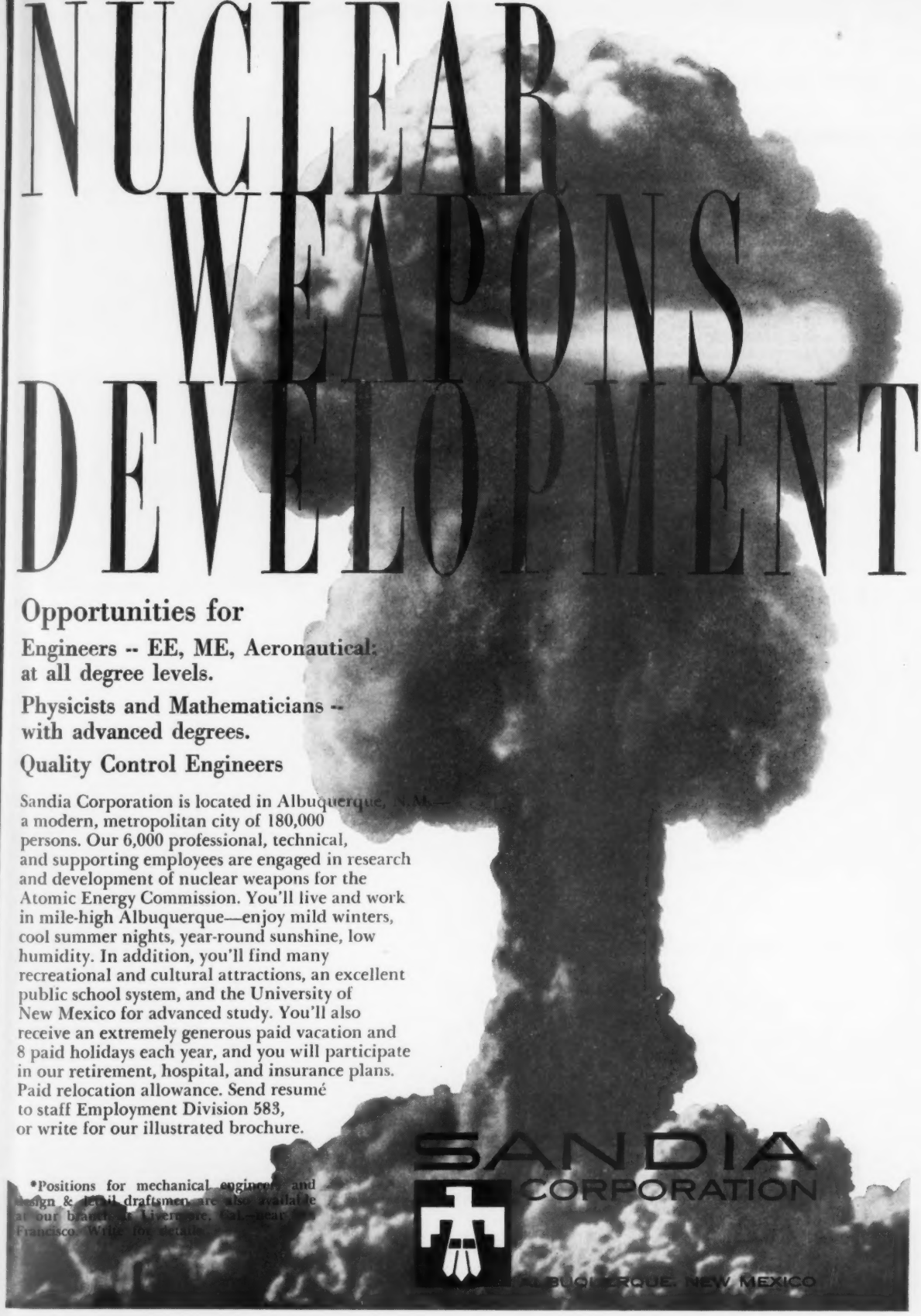
RESEARCH & DEVELOPMENT

• Northrop Aircraft has developed an ear-like manometer accelerometer (see photo) for use on its Snark SM-62 intercontinental missile. Known as a flying plumb-bob, the glass device weighs about an ounce and is used to detect slight deviations in speed or position.

• Determination of the effects of radiation on hydrocarbon materials is the function of a new "hot" lab being completed by Southwest Research Center. Two cells are designed to handle 100,000 curies of Cobalt-60 gamma radiation. The $625,000 facility is a part of the Pratt & Whitney nuclear aircraft propulsion program.

• Another atomic project is concerned with the effects of radiation on electronic

NUCLEAR WEAPONS DEVELOPMENT



Opportunities for

Engineers -- EE, ME, Aeronautical; at all degree levels.

Physicists and Mathematicians -- with advanced degrees.

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Sandia Corporation is located in Albuquerque, N.M.—a modern, metropolitan city of 180,000 persons. Our 6,000 professional, technical, and supporting employees are engaged in research and development of nuclear weapons for the Atomic Energy Commission. You'll live and work in mile-high Albuquerque—enjoy mild winters, cool summer nights, year-round sunshine, low humidity. In addition, you'll find many recreational and cultural attractions, an excellent public school system, and the University of New Mexico for advanced study. You'll also receive an extremely generous paid vacation and 8 paid holidays each year, and you will participate in our retirement, hospital, and insurance plans. Paid relocation allowance. Send resumé to staff Employment Division 583, or write for our illustrated brochure.

*Positions for mechanical engineers and design & detail draftsmen are also available at our branch in Livermore, Cal.—near San Francisco. Write for details.

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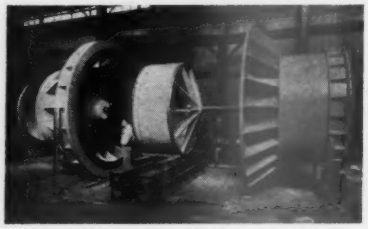
MINNEAPOLIS **Honeywell**

AERONAUTICAL DIVISION

components of atomic rockets and space satellites. The Admiral Corp. on work for the Air Force, is "cooking" various materials in a nuclear reactor for six-day periods.

• A large air flow control valve (see photo) has been delivered to North American Aviation for use in their blowdown wind tunnel. The 13-ft-OD, 15-ft-long, 34-ton valve was built by Pittsburgh–Des Moines Steel Co. Designed for a maximum flow of 40,000 cfps, the valve regulates downstream pressures from 5 to 100 psi at a maximum upstream pressure of 132 psi. It features a stainless steel metal-to-metal seat with a hydraulic, longitudinal moving plug.



• Rocket catapults will be tested by Talco Engineering Co. (Hamden, Conn.) at their new facility at North Branford. Cartridge-actuated devices will be run on a 200-ft and a 25-ft track. The company uses CAD's for emergency aircraft personnel ejection.

• New Advanced Engineering Center at Baltimore provides Bendix with an additional 100,000 sq ft of space for projects on guided missiles and radar. About 400 engineers will man the facility.

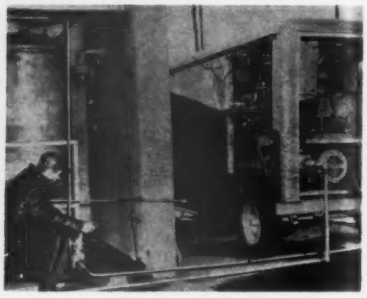
• Douglas Aircraft Co. engineers believe that by the time jet transports go into service, the roar of jet engines will be muffled to acceptable levels. The three methods of suppressing noises are shifting frequencies, altering the mixing of exhaust with air, and reducing the exhaust velocity. An ejection device—a cylinder extending beyond the tailpipe—combined with a mixing nozzle has resulted in the most satisfactory noise reduction yet.

• Simulation of altitudes above 150,000-ft is possible at the new Wright-Patterson AFB space chamber which has vacuum pumps that can create high altitude conditions in a few seconds. The 46-ton tank can handle personnel and large equipment. In addition to the main tank, there is a one-man chamber using an F-86 cockpit, and an animal chamber which can be rotated in any position.

• World-wide cosmic radiation intensity is being mapped by a globe-trotting KC-97 loaded with a 1500-lb cosmic ray monitor. The Air Force expedition will fly at an altitude of 18,000 ft and zig-zag around the world 1000 miles on either side of the equator. Tests will help determine twist of the earth's magnetic field.

• Union Carbide and Carbon Corp. (New York) has developed a silicone rubber that will conduct electricity without wires. Tagged X-1516, the material is expected to find high temperature applications in the aviation field.

• To simulate temperature extremes encountered in missile flight, Reaction Motors, Inc. (Denville, N. J.), has designed and built three heating and air conditioning plants. Equipped with industrial Dravo Corp. heaters having an output capacity of 250,000 Btu per hour, the units are set on four-wheel trailers (see photo), can be moved where needed.



• American Silver Co. (Flushing, N. Y.) hopes to facilitate experimental and development work on honeycomb structures for aircraft and missiles with its new titanium strip which it is now making in thicknesses down to 0.001 in.

• Beckman Instruments, Inc. (Fullerton, Calif.), has begun development of a high speed electronic data processing system, capable of recording up to 5000 pieces of test information per second, for Westinghouse Electric Corp.'s Aviation Gas Turbine Division.

• Following a pattern set by other aircraft and missile firms, Lockheed Missile Systems plans to "plunge deeply into atomic research," is seeking a nuclear facility for its new Palo Alto (Calif.) research laboratories.

• Douglas Aircraft is building a new test facility on a 1715-acre site in the Sacramento (Calif.) area. The facility will be used for development work on the USAF Thor IRBM.

ARS Meetings Calendar

—1957—

April 3–5: ARS Spring Meeting, Sheraton Park Hotel, Washington, D. C.

June 9–13: ARS Semi-Annual Meeting, Hotel St. Francis, San Francisco.

Aug. 25–28: ARS-Northwestern Technological Institute Gas Dynamics Symposium, Northwestern University, Evanston, Ill.

Dec. 2–6: ARS Annual Meeting, New York.

An Invitation to Serious-Minded ENGINEERS and PHYSICISTS

At the new and modern Burroughs Research Center in beautiful suburban Paoli, Pennsylvania, our engineers and scientific personnel are serious minded men . . . they are devoting FULL time to actual creative accomplishment. No excessive paperwork, dulling routine or unnecessary work duplication hinders them from the FULL utilization of their varied talents and creative potentials.

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If you want to build a solid lifetime career and assume the complex responsibilities involved with work on ICBM, SAGE and other important electronic programs for both government and industry, may we urge you to look into the Burroughs story if you qualify as —

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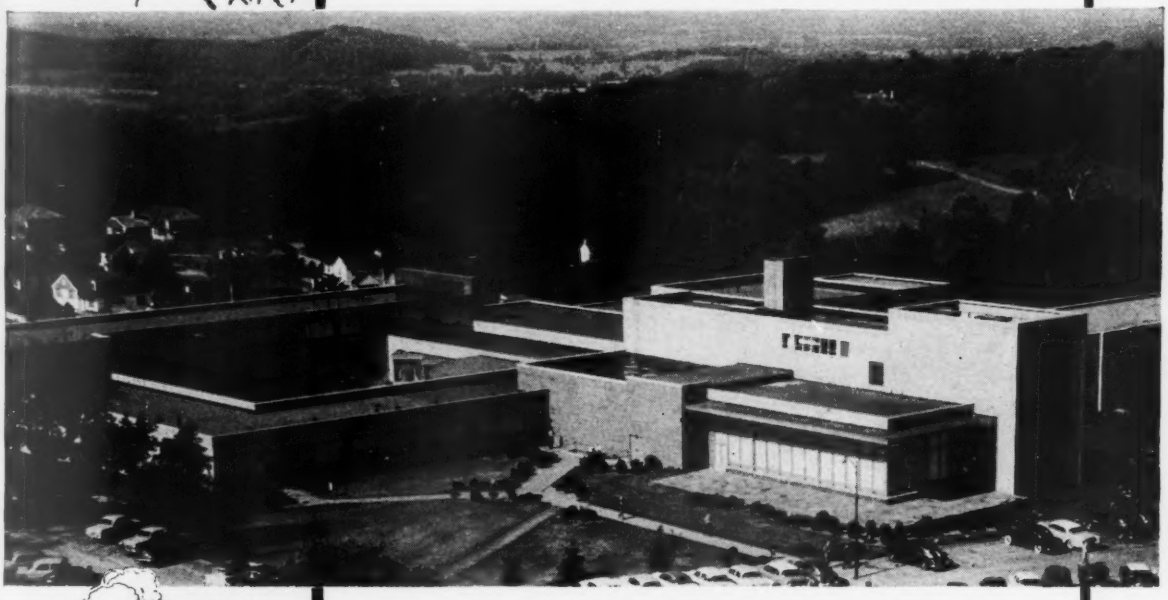

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An effective combination of design, know how and precise workmanship have made available this linear actuator. This rugged, compact, dependable unit has proven able to perform under the most adverse conditions and temperature changes.

In this particular design, overloads on the drive tube, in both directions of the stroke, actuate a short stub shaft, compressing the spring and operating a limit switch which is connected to the power source.

New heights of performance demand new standards of precision and dependability. Bring your next actuator design problem to us.

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Gear teeth get in line when he takes a hand

R. L. Thoen, right, explains faulty tooth conformation on a minute gear which has been enlarged 100 times in this king-sized projector. Gear specialist on the engineering staff of the Mechanical Division of General Mills and author of numerous technical papers, Thoen makes gear trains perform with uncanny accuracy. He helps design and build the special machines which make such accuracy routine work at the highly specialized plant.

Next to its men, General Mills is most proud of its machines. For it is this combination that mass produces gear trains with nearly imperceptible backlash, total cumulative error of 0.0002 inch, angular tolerances within 40 seconds of arc, positioning accuracy within 0.01 percent.

This typical General Mills precision production is possible only because men like Thoen have improved standard tools, created special machines, devised ingenious attachments. Some equipment is operated under strict temperature-humidity control. All is backed with the finest inspection devices. You can use these machines and the men that created and operate them to produce your precision products. You'll profit. A simple request brings more facts.

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Learn how our men and machines eliminate irksome production problems. Write Dept. JP12, Mechanical Division of General Mills, 1620 Central Ave. N.E., Minneapolis 13, Minn.

General Mills Pioneers Scientific Frontiers One of General Mills' numerous research projects involves the behavior of metals in space flight. Here a scientist determines the "sputtering" or disintegration rate of molybdenum at 200 miles above the earth. The metal is under fire from atoms moving at 25,000 m.p.h.

MECHANICAL DIVISION OF General Mills

CREATIVE RESEARCH AND DEVELOPMENT + PRECISION ENGINEERING AND PRODUCTION

U. S. Air Force Photo

Designed basically for night photographic work, the Martin RB-57 is employed by USAF TAC, powered by two Wright J-65 jet engines.

WADC'S WEAPONS GUIDANCE LABORATORY GIVES ACCURACY TO AIR FORCE BOMBS, MISSILES AND AIRCRAFT

The Weapons Guidance Laboratory at the Air Research and Development Command's Wright Air Development Center performs applied research and development of all Air Force weapons guidance equipment.

Included under this broad category are airborne bombing systems and equipment, weapon defense systems, offensive fire control systems, missile guidance equipment, electronic jamming systems, chaff systems, navigation systems, manual navigation aids and special test equipment peculiar to the requirements of the weapons guidance systems or equipment. In addition, all components of the foregoing are the province of this laboratory. The facilities available for these studies include various gun ranges, temperature and altitude chambers and other specialized test and evaluation installations.

Weapons Guidance is one of the laboratories that form the Wright Air Development Center. WADC, in turn, is the largest Center under the Air Research and Development Command. At its location at Wright-Patterson Air Force Base, Ohio, upward of 10,000 military and civilian workers are engaged in research, development and testing of aircraft, guided missiles and all types of associated flight and ground equipment.

This is one of a series of ads on the technical activities of the Department of Defense.

105

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Engineer of Ford Instrument Company checking unit designed by the Company for the Air Force to be certain that its magnetic effects will not affect other instruments in the aircraft.

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ARS News

Sections

Columbus: Abbott A. Putnam, assistant division chief of Thermodynamics and Aerodynamics at Battelle Memorial Institute, was the featured speaker at the Section's October 11 meeting. Mr. Putnam's subject was "Combustion Problems Associated With Rocket Engines."

Fort Wayne: Richard M. Holl is the new Section secretary. He replaces Paul W. Kruse.

Indiana: M. J. Zucrow of Purdue University was the principal speaker at the Section's first meeting of the 1956–1957 year which was held at Purdue on October 11. Dr. Zucrow discussed the problems encountered in the design and use of rocket engines, stressed the lack of basic knowledge necessary for intelligent design of rocket power plants for different applications.

On October 16, Robert W. Graham of Lewis Flight Propulsion Laboratory discussed "Aerodynamic Heating and the Re-entry Problem" at the Section's second session of the season. Dr. Graham talked about the effect of flight speed and missile configuration on aerodynamic heating and about research going on at the Lewis Flight Propulsion Laboratory.

Bell Dead

Lawrence Dale Bell, 62, founder and chairman of Bell Aircraft Corp., died October 20 of a heart ailment, in Buffalo, N. Y. An aviation pioneer, Mr. Bell made many contributions to the development of aircraft and guided missiles during his 45 years in the aviation field. Mr. Bell was a Fellow Member of the AMERICAN ROCKET SOCIETY.

Philadelphia: On October 16, the Section received its charter from ARS Director Andrew G. Haley. Another ARS director, Wernher von Braun, was the featured speaker at the presentation. Pictured with Dr. von Braun, above, are Dr. Burlew (left), executive vice-president of Franklin Institute, and Abe Bernstein (right), Section president.

Pacific Northwest: On September 5, Section members met in the University of Washington Auditorium, listened to Allen G. Schinn speak about inertial navigation systems. Mr. Schinn, a research specialist in the instrument development group of Boeing Airplane Co.'s Pilotless Aircraft Division, is shown (above) flanked by Program Director Emmett W. Coon (left) and Section President J. C. Drury (right).

Twin Cities: Approximately eighty persons attended the first meeting of the newly reorganized Twin Cities Section on October 11, at the University of Minnesota.

Dean Athelstan Spilhaus of the University of Minnesota's Institute of Technology spoke on "The Relation of the Satellite Program to the International Geophysical Year." Dr. Spilhaus is a member of the Earth Satellite Program committee of IGY.

New York Section Visits Nike Site

Missiles have come a long way since G. Edward Pendray (top) helped found the AMERICAN ROCKET SOCIETY 26 years ago. On a recent visit (JET PROPULSION, Nov., p. 1016) to Battery B, 66th AAA Missile Battalion, Dr. Pendray and other members of the New York Section had an opportunity to measure missile progress as they inspected part of the Nike ring guarding New York City. In the course of the visit, Section President Charles J. Marsel (bottom) found time to discuss some finer points of rocket engine design with Lt. Colonel Arthur L. Meyer, Battalion Commander and host.

Sacramento Takes Title

Frank Coss, president of the recently formed Sacramento Section, receives charter from ARS Vice-President, Commander Robert Truax. Following the presentation, Commander Truax talked about "Early Liquid Rocket Development in the Navy" and showed films of early tests at U. S. Naval Engineering Experiment Station at Annapolis.

New Patents

George F. McLaughlin, *Contributor*

Automatic Valve (2,754,656). William P. Munger, Far Hills, N. J., assignor to Reaction Motors, Inc.

Jet propulsion engine with pulse jet units (2,750,733). F. G. Paris, J. LeFoll, J. H. Bertin, and M. J. Barout, Montgeron, France, assignors to Société Nationale d'Étude et de Construction de Moteurs d'Aviation.

Forwardly facing inlet spaced from the end of the exhaust, a rearwardly facing outlet, and a closed pressure chamber toward the rear of the engine.

Explosive jettison device for airborne stores (2,750,842.) Walter H. Myers, Chalfont, Pa., assignor to the U. S. Navy.

Detonation of an explosive charge within a firing chamber sequentially displacing a retaining member from its first extreme position, and then forcibly displacing a stud member from its seated position within a cylindrical recess.

Reaction chambers for the decomposition of monofuels (2,751,750). D. F. Welch and I. G. Strang, Rugby, England, assignors to The British Thompson-Houston Co., Ltd.

Atomized fuel is introduced into an auxiliary reaction chamber so it impinges on a heater. A transfer conduit leads from the chamber into the main reaction chamber.

Thrust controlled mechanism for jet propelled aircraft (2,757,510). Robert L. Holloway, Snyder, N. Y., assignor to American Machine & Foundry Co.

Flow of gas from adjacent jet exhausts is simultaneously deflected angularly to move in a direction opposite to the flow of undeflected gases.

Glow plug ignitor structure (2,758,441). Emil O. Kalil, Sidney G. Rumbold, and Douglas G. Van der Pool, Bloomingdale, N. J., assignors to The M. W. Kellogg Co.

Cylindrical body containing a heating element for initiating combustion of a plurality of fluid propellant components.

Calibrating apparatus [installed in a jet engine] (2,785,469). Claude W. Clements and Wayne P. Fanyo, Riverside, Calif., assignor to General Dynamics Corp.

Heating members mounted upon a thermocouple system to simulate heat conditions generated in the tail cone during jet engine operation.

Blast deflector for jet propelled aircraft (2,758,805). Connelly L. Graham, Covina, Calif., assignor to Northrup Aircraft, Inc.

Movable vertical fairings, hinged aft of the exhaust of jet engines converging at the rear of the fuselage, deflect the jet blast laterally in opposite directions.

Explosive cartridge retraction of landing gear (2,758,807). Stanley Ryan, Long Beach, Calif., assignor to Northrup Aircraft, Inc.

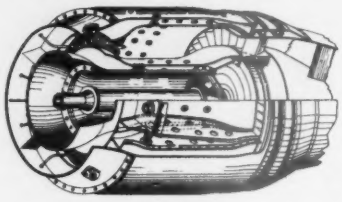
Telescopic members of a landing gear arranged so the breach may be exposed to enable a spent cartridge to be removed and a fresh cartridge loaded.

Lift rotor control (2,759,548). Shao Wen Yuan and Theodore Von Kármán, Pasadena, Calif.

A boundary layer control, including suction means, extending along movable flaps at the trailing edges of the rotor blades of a rotary wing aircraft.

Parachute delayed opening means for free fall containers (2,759,693). Reinhold Gross, Dayton, Ohio.

Means outside a container for igniting a time delayed explosive charge and releasing the cover of a parachute compartment.



2,760,338

Jet engine fuel control apparatus (2,760-337). B. H. Ciscel and E. C. Petry, Minneapolis, Minn., assignors to Minneapolis-Honeywell Regulator Co.

Control response which operates when the indicated speed is different from the selected speed by a predetermined amount.

Annular combustion chamber for gas turbine engine (2,760,338). Francis Henry Keast, Toronto, Canada, assignor to A. V. Roe, Canada, Ltd.

Flame tube, supported between inner and outer casings, divided longitudinally into a plurality of combustion zones with partitions defining fluid passages.

Camera for recording the yaw of a spin stabilized projectile (2,759,785). Wm. R. Smythe and Ira S. Bowen, Altadena, Calif., assignors to the U. S. Navy.

A moving spool of film strip confronts a pinhole in the head of a prespun missile adapted to face the sun at every revolution. A mass coaxial with the head holds the film and is inhibited by inertia from spinning with the missile.

Apparatus for continuously feeding a liquid fuel and a liquid fuel oxidizer to a combustion chamber of propulsion type (2,760,-335). Robert H. Goddard, deceased, by Esther C. Goddard, Executrix, Worcester, Mass., assignor one-half to the Daniel and Florence Guggenheim Foundation.

Liquid oxidizer is supplied under pressure to an outer jacket space, and an inner jacket space has openings through which part of the liquid is sprayed against the combustion chamber wall.

Powder reactor (for rockets) including a perforated conical grid (2,759,326). E. W. Brandt, Geneva, Switzerland, assignor to Anstalt fur die Entwicklung von Erfindungen und gewerblichen Anwendungen Energa.

A grid within a chamber is interposed between the propelling charge supported in its front end, an igniter of high calorific power in its narrowest part, and a series of nozzles at the rear.

Welded end closure means for rocket motors (2,762,193). Carl E. Johnson, Verona, Pa., assignor to Scaife Co.

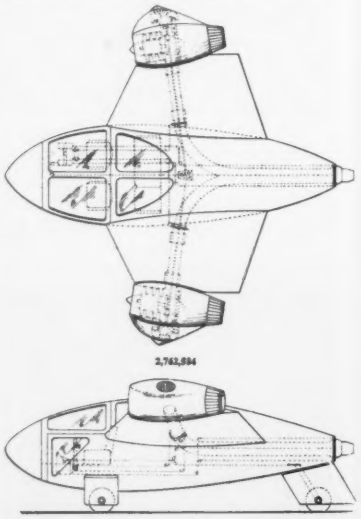
Heat insulator in a container between the end closure and the charge of ignitible gas generating material. During welding, the temperature of the container adjacent to the charge nearest the end closure is less than the ignition temperature of the charge.

Method of operating a turbojet engine (2,765,617). Earle W. Gluesenkamp and Milton Kasmin, Dayton, Ohio, assignors to Monsanto Chemical Co.

Method comprises feeding into the combustion chamber a mixture of air and hydrogenated polycyclic hydrocarbon having a specific gravity of from about 0.85 at 30 C to about 1.5 at the same temperature, a pour point above 5 C, and a heat of combustion of at least 125,000 Btu/gal.

Fuel feeding to resonance type jet propulsion engines (2,765,618). Robert E. Houle, Willimantic, Conn.

Mixture of air and fuel produces a standing shock wave in the combustion chamber. A pulsing flow of fuel has periods of flow at the same frequency as the occurrence of elevated pressures in the chamber, and quantities proportional to the amplitude of the elevated pressures.



2,762,584

Vertical rising road operable aircraft (2,762,584). Nathan C. Price, Hollywood, Calif., assignor to Lockheed Aircraft Corp.

Turbine engines for generating propulsive streams of compressed air are pivoted in pods at the wing tips. Pods may be differentially moved about the spanwise mean axis of the wing to discharge air in any direction at right angles to the wing axis.

Means for controlling the direction of a stream of ionized fluid (2,763,125). Marcel Kadosch and Louis de Jurquet de la Salle, Paris, France.

A negatively charged electrode on the inner wall of a reaction jet tube, and a positively charged electrode in the tube provide a potential gradient transverse to the ionized stream whereby ions cause part of the stream to deviate outside the boundary of the stream. A member deflecting the stream portion passing into the direction of flight produces a steering or braking action.

EDITOR'S NOTE: The patents listed above were selected from recent issues of the Official Gazette of the U. S. Patent Office. Printed copies of patents may be obtained at a cost of 25 cents each, from the Commissioner of Patents, Washington 25, D. C.

35 ton bomber gets carrier shakedown

Largest and most powerful aircraft ever to operate from a carrier deck, the Douglas A3D Skywarrior has now completed landing and takeoff tests aboard the U. S. S. Forrestal—the Navy's mightiest carrier. Able to deliver the A-bomb, at speeds above 600 mph, Skywarrior is designed to extend our carrier's striking range beyond any point yet reached.

U. S. Navy's atom bomber, the Douglas A3D Skywarrior

Continued advances in naval aircraft are meaningless without skilled fliers at the controls. If you are interested in a career as a Naval Aviator, drop a card today to *Nav. Cad., Washington 25, D. C.*

Depend on *DOUGLAS* First in Aviation

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Aerodynamics & Propulsion

APL-An Organization Of And For Technical Men And Scientists

The Applied Physics Laboratory, (APL) of the Johns Hopkins University is an organization of and for technical men and scientists. APL is organized on a horizontal basis; responsibility and authority are given in equal measure. Scientists and technical men occupy all decision-making positions, because our *only* objective is technical progress.

Because of its predominantly professional character, APL has kept in the vanguard, having pioneered the proximity fuse, the first supersonic ramjet engine, the Navy's Bumblebee family of missiles which includes the TERRIER, TALOS and TARTAR, and is presently attempting break-throughs on several important fronts.

Occupying a site equidistant from Washington, D. C., and Baltimore, Maryland, APL's new laboratories allow staff members to select urban, suburban or rural living, and either of these outstanding centers of culture as a focal point for fine living. Salaries compare favorably with those of other R & D organizations.

OPENINGS EXIST IN:

DEVELOPMENT: Stability and analysis; ramjet engine design; preliminary design and wind-tunnel testing.

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Equipment

Electrical

Missile Motor. Controls brake-flaps. Weighs $2^1/_2$ lb. Electro-mag brake stops and locks output shaft within 60 deg of rotation after circuit break; 18 amp, 28 v dc, 0.208 hp. Motronics Corp., 241 Concord, Glendale, Calif.

Small Load Cells. SR-4 type of 50-, 100-, and 200-lb capacity. $3^1/_4$ in. high by $3^1/_2$ in. diam. Baldwin-Lima-Hamilton Corp., Electronics & Instrumentation Div., 806 Massachusetts Ave., Cambridge 39, Mass.

Angular Accelerometer Calibrator. Model AA C-2 for range of 0.5–140 radians/sec^2. Statham Development Corp., 12411 W. Olympic Blvd., Los Angeles 64, Calif.

Quartz Lamp Oven Sections. Provides temp of over 1000 F. Fostoria Pressed Steel Corp., Fostoria, Ohio.

Silicon Diode. Available in 600, 800, 1000 v with current output of 125 ma. International Rectifier Corp., El Segundo, Calif.

New Transistors. MAT of micro alloy is ten times faster than fastest vacuum tube in electronic computers. SBDT is surface barrier, diffused type and will operate at 500 megacycles. Philco Corp., 4700 Wissahickon Ave., Philadelphia, Pa.

Inverter-Amplifier. Low drift d-c unit for use with strain gages, load, pressure, acceleration transducers. Allegany Instruments Co., Cumberland, Md.

Accelerometers. For vibration measurement systems. Can be used as primary standard. Dynamic g ranges of 0.001–2000; frequencies of 10–80,000 cps. Massa Laboratories, Hingham, Mass.

Wide-Band Power Oscillator. Covers 200–2500 Mc/sec. Models with wattages of 10–40. Maxson Corp., 47-37 Austell Place, Long Island City 1, N. Y.

Miniatures. New line includes voltage standard, acceleration switch, and 5-amp SPST relay. Hermetically sealed pixie case less than 1 cu in. Cook Electric Co., 2700 Southport Ave., Chicago 14, Ill.

New Oscillograph. Type 5-119 features flash timing system for absolute synchronization and explosion-proofing for airborne applications; 400-cycle, 200-v, three-phase operation only. Up to 100 units can be slaved by timing system. Consolidated Electrodynamics Corp., 300 N. Sierra Madre Villa, Pasadena, Calif.

Mechanical

Flexible Tubing. Plica Type-A is all-metal, liquid-tight up to 560 F and 60 psi; $^3/_8$- to 2-in. sizes. Flexaust Co., 100 Park Ave., New York 17, N. Y.

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Continuous Mixer. Anthony Mixer, adaption of single-shaft pug mill. Handles 20–30 yards/hr. Gas Machinery Co., 16100 Waterloo, Cleveland 10, Ohio.

Cylindrical Grinder. Heavy-duty model handles workpieces up to 6500 lb on centers. Available as semi-automatic. Norton Co., Worcester 6, Mass.

Self-Balancing Scale. 5000-gram or 11.4-lb capacity. Reads to 1 gram or 0.01 lb. Arthur S. LaPine & Co., 6001 S. Knox, Chicago 29, Ill.

Tension Gage. Tests springs. Four models, 0–150 gram. P. K. Neuses, West Euclid & Dwyer St., Arlington Heights, Ill.

Flexible Couplings. Rubber construction with torque capacities of $^1/_{80}$ to 3500 hp. Lord Mfg. Co., 1635 W. 12 St., Erie, Pa.

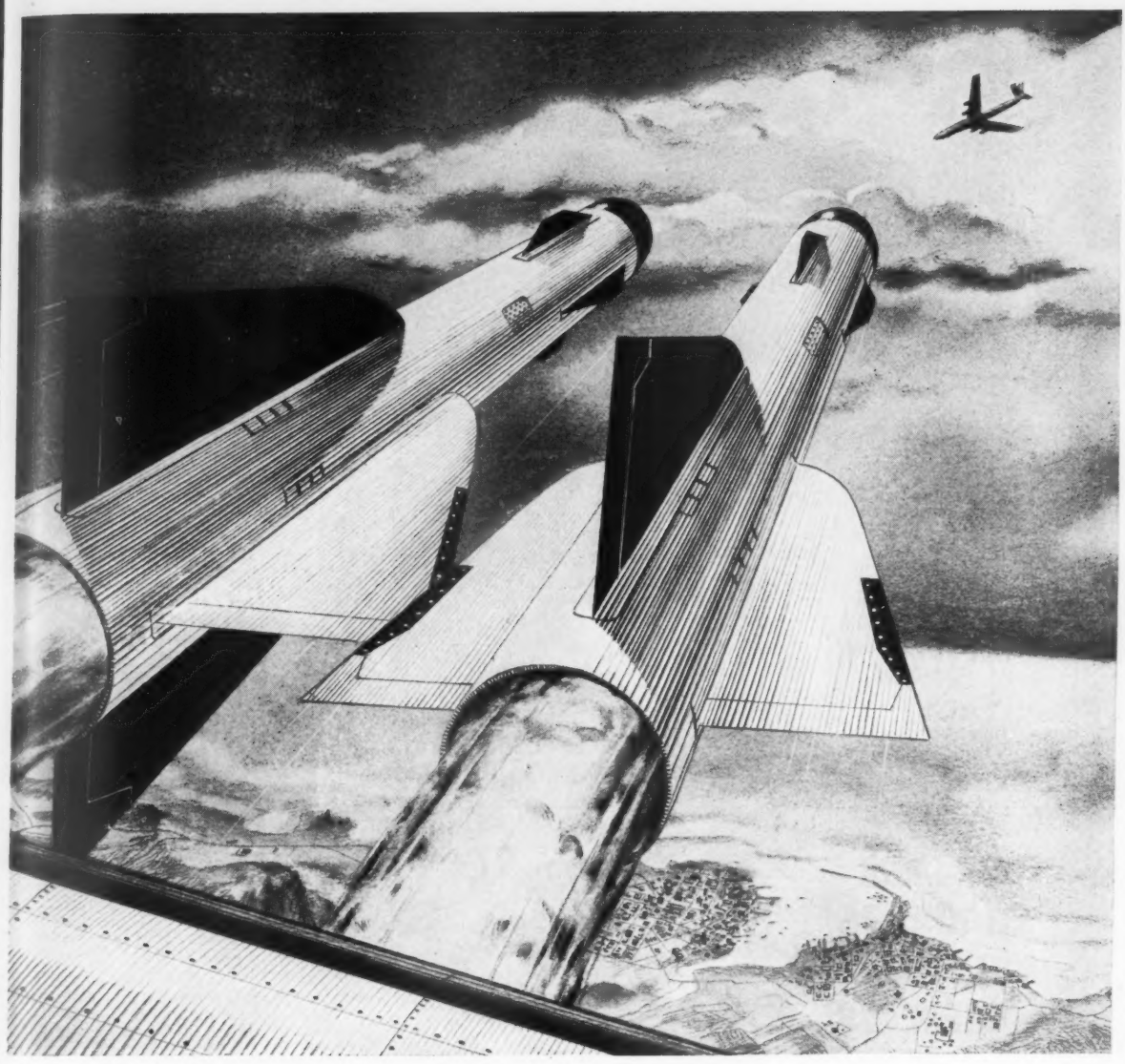
Missile Fan. Miniature, 4 oz Aximax II gives 1¼ w fan output. Rotron Mfg. Co., Schoonmaker Lane, Woodstock, N. Y.

Check Valve. For lox, fuming nitric acid at temp from −320 to 450 F; 0–5000 psi seal with low pressure drop. Precision Equipment Co., 1641 Border Ave., Torrance, Calif.

Relief Valves. For missile, rocket, aircraft use. MIL-V-5523C specs: full flow inlet pressure of 4050 psi, back pressure 200 psi. Waterman Engineering Co., 725 Custer Ave., Evanston, Ill.

Baby Turbojet. Miniature gas turbine (AS-18 Fuel-Air Turbostarter) weighs 46 lb, is $12^1/_4$ in. long, has diam. of $8^3/_4$ in. Used to start large turbojet engines in 20–25 sec. General Electric Co., Schenectady 5, N. Y.

Flexible Connector. Designed for end-



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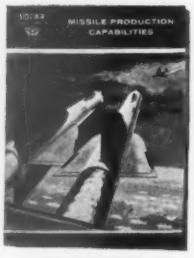

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Fluid-Tight Rivet. Self-sealing aluminum alloy with single shear of 573-1473 psi for $^5/_{32}$ to $^1/_4$-in. diam. Pastushin Industries, 5651 West Century Blvd., Los Angeles 45, Calif.

Test

Proving Ring Dynamometer. Type TDC-4 is a force-sensitive transducer which is available in ranges of 0–100 lb to 10,000 lb. Displacement of about 0.03 in. with a full-range output of 0.25 v with 6.3 v, 60 cps input. Linearity of ±0.1% with less than 0.5% hysterisis. Schaevitz Engineering, Crescent Blvd. at Drexel Ave., Pennsauken Turnpike, Camden, N. J.

Spectrograph. Spec-Lab features 4-in. Pyrex disk, with 3-meter radius of curvature. 15,000 and 30,000 lines/in. $2^1/_2$- by $1^5/_8$-in. ruled area. 1800–9600 A range. 20-in. spectrum, resolves 0.1 A. Jarrell-Ash Co., 26 Farwell St., Newtonville, Mass.

Boresight Camera. 35-mm camera has 40-in. lens and radar secondary mount. Photographs target being tracked by radar set. Thyratron pulse drive unit. Picture speeds up to 10/sec. Cameraflex Corp., 1947 Broadway, New York 23, N. Y.

Instrumentation Camera. Type 232 Mk. 7 features automatic operation on 35-mm film. 100-ft magazine. Exposes $^1/_{100}$ sec at 3 cps. **Automatic Film Processor.** For 16, 35, or 75 mm film. Processes & dries at $1^1/_2$, 3, or 6 fpm. Norden-Ketay Corp., 99 Park Avenue, New York, N. Y.

High Speed Camera. Model 500 is 16 mm, has 100 and 200 fps operation. Exposure of $^1/_{1000}$ sec. 28 v dc or 115 v ac. Triad Corp., 4515 Sepulveda Blvd., Sherman Oaks, Calif.

Ultrasonic Flowmeter. Measures mass, volume, handles up to 720,000-lb JP at 1% accuracy. W. L. Maxson Corp., 47-37 Austell Pl., Long Island City 1, N. Y.

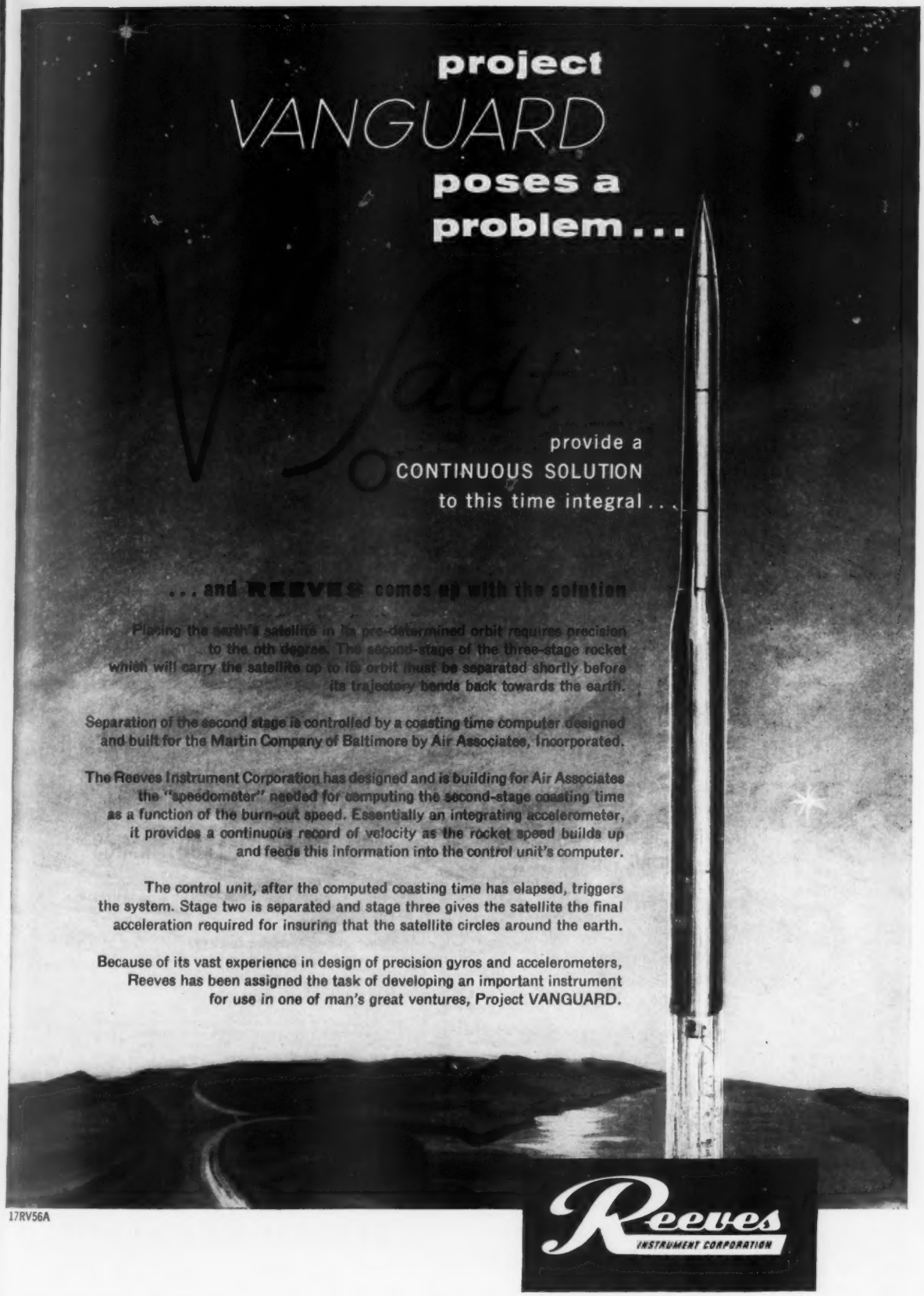
Calibrator. For wire strain gages, transducers, thermocouples. Type C will calibrate 1-, 2-, or 4-arm systems. Accuracy is ±0.1%, Allegany Instrument Co., 212 Durham Ave., Metuchen, N. J.

Radiant Heat. Infrared lab unit is 16 in. deep with opening of $13^1/_2$ in. Holds eight 1600-w quartz lamps. Load is 12.8 kw. 97% reflection gives 1000 F temp. Fostoria Pressed Steel Corp., Fostoria, Ohio.

Processes

A giant electronic shield 40 ft long, 35 ft wide, and 18 ft high was recently made to check out the new Air Force GAM-63 surface-to-air guided missile. Built by Ace Engineering and Machine Co., Philadelphia, it sheds light on the size of the yet classified missile. Set up at Bell Aircraft Corp., Buffalo, N. Y., the door is 21 ft wide and 16 ft high. The box was used to provide a positive radio frequency seal and is checking out Rascal and its ground support equipment prior to delivery to Holloman AFB before firing.

(Continued on page 1134)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Placing the earth's satellite in its pre-determined orbit requires precision to the nth degree. The second-stage of the three-stage rocket which will carry the satellite up to its orbit must be separated shortly before its trajectory bends back towards the earth.
Separation of the second stage is controlled by a coasting time computer designed and built for the Martin Company of Baltimore by Air Associates, Incorporated.
The Reeves Instrument Corporation has designed and is building for Air Associates the "speedometer" needed for computing the second-stage coasting time as a function of the burn-out speed. Essentially an integrating accelerometer, it provides a continuous record of velocity as the rocket speed builds up and feeds this information into the control unit's computer.
The control unit, after the computed coasting time has elapsed, triggers the system. Stage two is separated and stage three gives the satellite the final acceleration required for insuring that the satellite circles around the earth.
Because of its vast experience in design of precision gyros and accelerometers, Reeves has been assigned the task of developing an important instrument for use in one of man's great ventures, Project VANGUARD.
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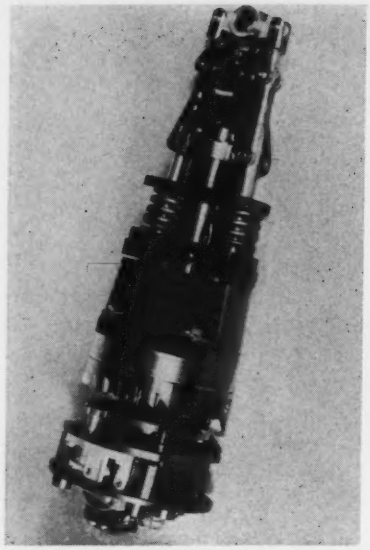
REEVES INSTRUMENT CORP. *A SUBSIDIARY OF DYNAMICS CORP. OF AMERICA,* 215 EAST 91st ST., NEW YORK 28, N. Y.



Recently declassified is a missile control surface pulser by Hanson-Goroll-Brian, Inc., 85 Hazel St., Glen Cove, N. Y. The device imposes a series of bi-directional step functions on control surfaces of test missiles to establish flight characteristics. The device uses fifty .22-caliber blank cartridges firing alternately into a pair of opposed cylinders. Pistons convert developed gas pressure into rotary motion through linkage. Amplitude, duration, and time spacing of the square waves can be adjusted. Using .22 short blanks develops a hinge moment of 250-in-lb. Over-all size is $12^1/_2$ by $3^7/_8$ in.

Materials

Rubber & Plastic Lining Compounds. Sampler contains 11 specimens of lining materials. Automotive Rubber Co., 12550 Beech Rd., Detroit 39, Mich.

O-Rings. Synthetic rubber for MLO-8200 and OS-45 hydraulic fluids from −65 to +400 F. For static seals. Rubber Products Div., Parker Appliance Co., 17325 Euclid Ave., Cleveland 12, Ohio.

Teflon Products. Tapes, sheets, rods, tubes, gaskets, and fabricated specialties in pure Teflon or combined with glass fiber cloth base. Continental-Diamond Fibre, Newark, Del.

Pre-Impregnated Glass Cloth. Polyester or epoxy for laminates. Standard Insulation Co., 74 Paterson Ave., East Rutherford, N. J.

Coated Fabrics and Laminates. "Lectron" acrylic resin constructions for electrical insulation. Fibers of Orlon, Dacron, or glass. Fabrics Div., E. I. duPont de Nemours & Co., Wilmington 98, Del.

Research Chemicals. Rare earth oxides and salts in high purity. Nuclear Corp. of America, 2812 N. San Fernando Blvd., Burbank, Calif.

Reinforced Plastics. Custom-built ducts, tanks, etc., in modular polyglas (polyester). Modular Plastic Corp., 1635 Westminster, Detroit 11, Mich.

Welded Tubing. Carbon and low-alloy steel, stainless, in size ranges of $^1/_4$-in. OD to $5^1/_2$-in. OD. Various wall thicknesses. Standard Tube Co., 24450 Plymouth Rd., Detroit 39, Mich.

Titanium Wire Cloth. From coarse to 60 mesh sizes. Cambridge Wire Cloth Co. Cambridge, Md.

Magnesium-Thorium Sheet. HK-31A available in gages for 0.016 to 2 in. Good short time properties to 800 F, long time to 600 F. Dow Chemical Co., Midland, Mich.

High Density Ceramic. Withstands 2500 F, good shock-resistance. Available in rod, bar, rounds, or flats. Machined by carbide-tipped tools. Technion Design & Mfg. Co., 262 Mott St., New York 12, N. Y.

Teflon. Pipe, tubing, and rod is now being produced. Pipe is made to 4-in. diam; lined steel pipe to 2-in. diam. Haveg Industries, 900 Greenbank Rd., Wilmington 8, Del.

Silicone O-Rings. Now made in standard AN and MS molds. General Electric Co., Waterford, N. Y.

Product Literature

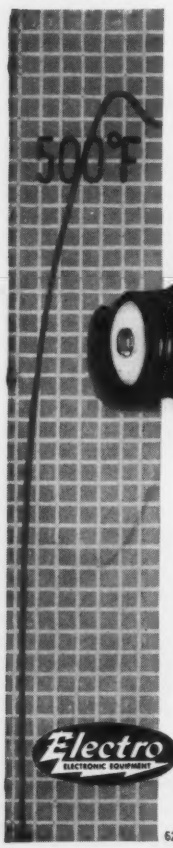
Rocket Engine Testing. Instrumentation for static tests is found in CEC Recordings for May-June 1956. Consolidated Electrodynamics Corp., 300 N. Sierra Madre Villa, Pasadena, Calif.

Thermocouple Assemblies. 1956 catalog presents line of products including wells, multiple wires, flex-tubes, and spring loaded devices. Conax Corp., 7811 Sheridan Drive, Buffalo 21, N. Y.

Testing. Bulletin 5101 covers test stands, instrumentation of thrust and pressure recording of jet propulsion engines. Baldwin-Lima-Hamilton Corp., Instrumentation Div., 806 Massachusetts Ave., Cambridge 39, Mass.

Jet Engine Flutter. Presents articles on research on flutter in June issue of *Engineering Research Reviews.* New York University, University Heights 53, N. Y.

(*Continued on page 1147*)



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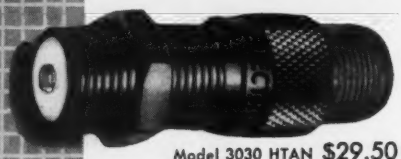

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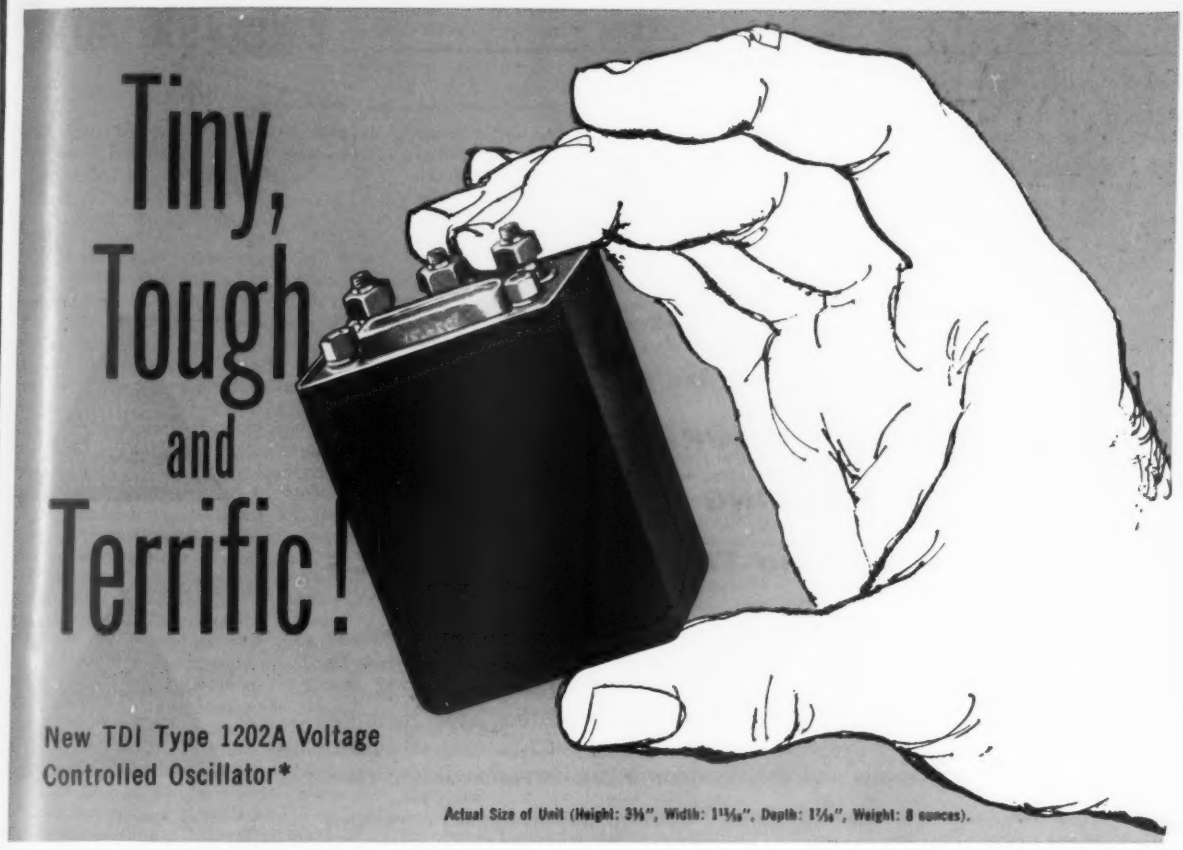
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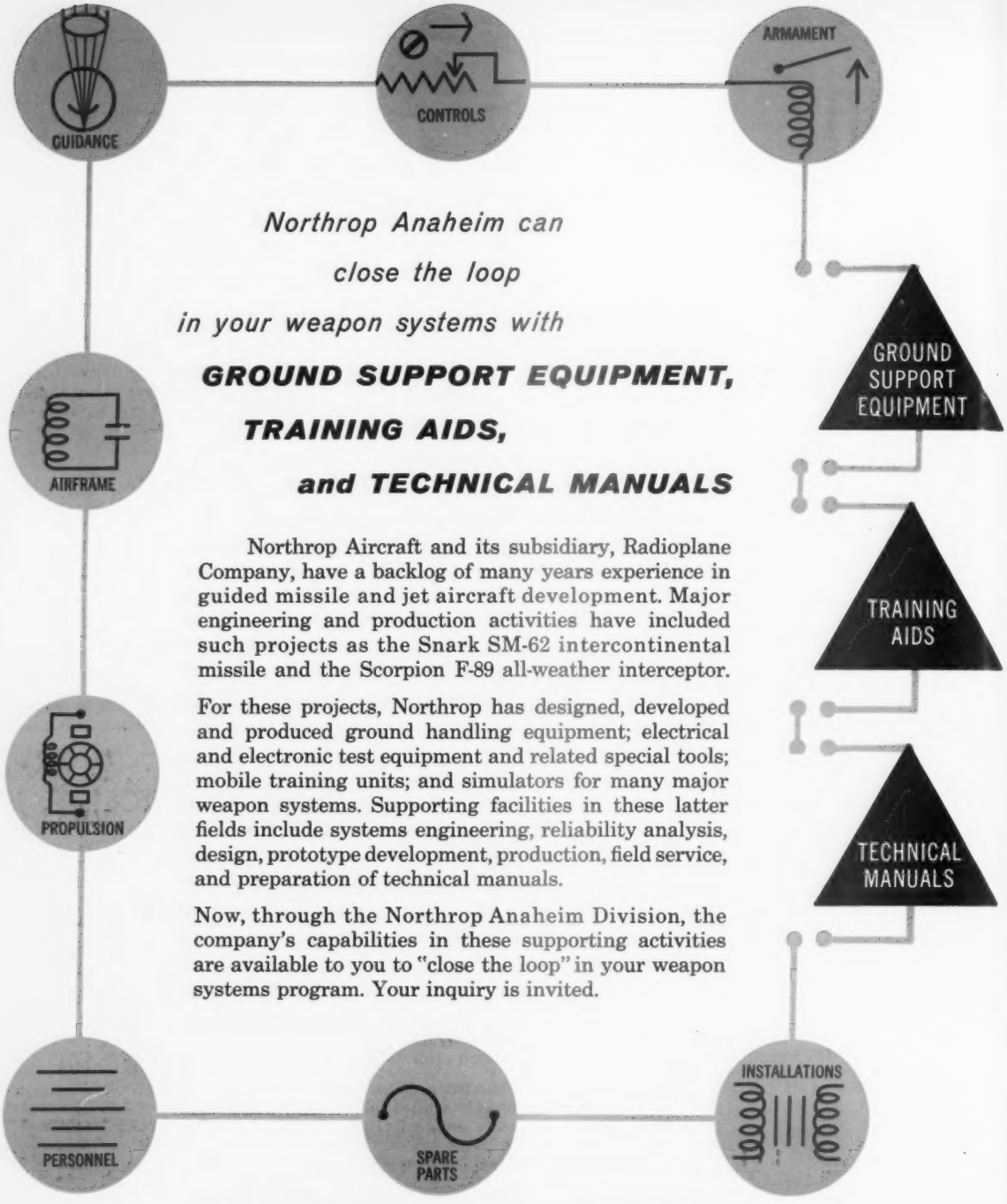

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Book Reviews

Ali Bulent Cambel, Northwestern University, *Associate Editor*

200 Miles Up, by J. G. Vaeth, Ronald Press, New York, 1955, 2nd edit., xiii + 261 pp. $5.

Reviewed by KURT STEHLING
Naval Research Laboratory

This edition of "200 Miles Up" is a semitechnical and interesting review of high altitude research. The author does not waste many pages on historical review; this phase has been adequately treated in other books. In the 13-chapter book he first discusses the behavior and characteristics of the upper atmosphere. Then follows a detailed treatment of some previous and current high altitude research rockets, including the instrumentation which is carried aloft by these vehicles. Indeed, the 40 pages devoted to upper air research instruments comprise the largest chapter in the book.

This book is also the first to review in considerable detail the present status of high altitude balloon research. Apparently it is not widely realized that plastic research balloons have carried and will carry many more pounds of instruments to high altitudes than such rockets as the Aerobee and Viking, which are also described airborne. These balloons are limited of course to an altitude of about 100,000 ft. It is in this region that these research vehicles have obtained much data.

A brief description is also given of one of the author's "pet" undertakings, Project FATSO (First Airborne Telescope and Spectrographic Observatory). This project represents a series of planned *manned* balloon flights during Mars opposition to the earth in 1956. Spectrographic and telescopic instruments, with two observers in a sealed gondola would be carried above 60,000 ft. With much of the turbulent atmosphere behind them, the observers would be able to photograph Mars, the sun, and other heavenly bodies in spectral regions and at a resolving power unheard of at sea level. An external swivelling mirror, controlled by the observer, would bring the image to the telescope if the gondola and balloon drift or rotate. One wonders why the entire gondola could not be suspended in a rotating bearing, controlled from inside and permitting a 360-deg scan.

Vaeth, in the last three chapters, reviews the Vanguard Satellite program which was announced before the book went to press. He asserts, correctly, that tracking of the satellite would prove to be a most difficult task. However, he concludes that the first rocket stage of the three required could be "little more than an improved V-2." Since V-2's are not available, a new first stage has to be designed and built. This is a very great difference in order of technical magnitude, from an "improved V-2." The author should have pointed out the large amount of work, planning, and study which such groups as the High Altitude Panel, the National Science Foundation and the AMERICAN ROCKET SOCIETY have undertaken for several years before the Vanguard announcement was made. The factor which was more important than the payload (the satellite) itself was the availability of the hardware which would lift any given payload into an orbit. The U. S. Navy's Viking had established a fine record of high altitude research and was thus naturally considered as a launching vehicle for a satellite. Similarly, many of the propulsion and guidance techniques developed for other missiles have been woven into Vanguard. Despite these past experiences, the vehicle department is a much greater task than the author implies.

The last chapter "Beyond the Earth" brings the reader from the humble beginnings of the small satellite to the grander objectives of interplanetary and interstellar journeys. The reader is shown the step-by-step approach to interplanetary flight. First the small satellite, then larger refueling satellites, and then manned space ships. The psychological and engineering problems which would be a part of such an undertaking are not ignored. It is stated that a "space ship simulator" would be one of the best ways to provide training for space ship crews. This simulator would reproduce, as much as possible, the anticipated environment in a space vehicle and would condition and train personnel.

The author claims that no very good purpose is served by claiming a military utility for orbital and space flight. He admits also that scientific utility alone is not sufficient at present to warrant a "crash" program, especially so, since military countermeasures by an enemy could negate our military satellite. However, the author might have added that few proposed military programs have ever been stopped because of possible countermeasures. Furthermore, military programs often lead to later nondefense applications which would not have been developed except for the often altruistic support by the military services.

The thirteen chapters of "200 Miles Up" present a comprehensive review of present high altitude research and the future possibilities of space flight. Although the author has perhaps tried to cover too much in 250 pages, he has at least given the reader a fresh approach to the subject and stimulated the serious reader to further reading.

Theory of Combustion Instability in Liquid Propellant Rocket Motors, AGARDograph no. 8, by Luigi Crocco and Sin-I Cheng, Butterworths Scientific Publications, London, 1956.

Reviewed by ADELBERT O. TISCHLER
Lewis Flight Propulsion Laboratory

AGARDograph 8 presents an analytical study of combustion-driven oscillations in

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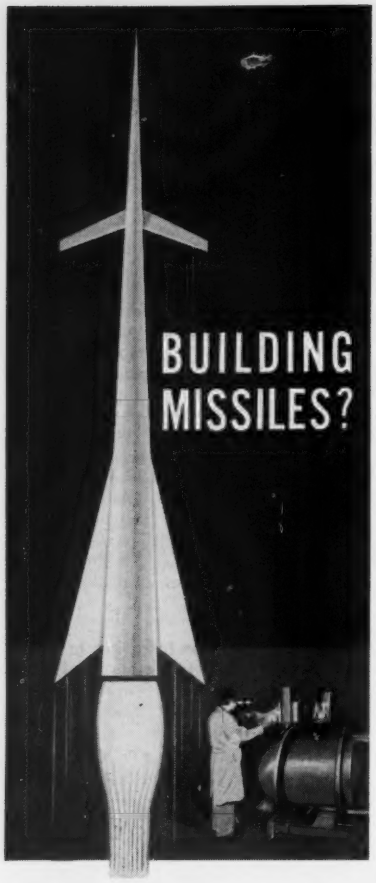

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rocket propulsion engines. This analysis is based on the concept of a combustion time lag which destabilizes the combustion system so that it continually "hunts," repeatedly overshooting the equilibrium operating point. It is a necessary part of this oscillatory system that the combustion reaction energize a disturbing factor that will in turn affect the combustion rate. The book describes several possible combustion-driven oscillatory systems.

The text consolidates several previous analytical treatments, and subjects a consistent set of initial assumptions to a systematic computational attack. The results provide a quantitative basis for the prediction of rocket combustion stability. Fifty pages are devoted to the well-recognized combustion system loop for the "chugging" phenomenon. Here the bipropellant case, as well as the monopropellant case, is analyzed; systems with constant rate of feed and systems with constant pressure feed are treated; servostabilization of the oscillations is discussed. Chap. 3 (70 pages) covers the longitudinal high frequency oscillation known as "screaming." In this chapter systems with concentrated combustion at arbitrary axial locations are treated, the effects of nozzle design and time-lag spread are analyzed, and the equations for arbitrarily distributed combustion are solved. The authors have included in Chap. 4 a discussion and comparison of their results with the limited available experimental data. The correlations obtained justify the approach used. Some of the detailed mathematical intricacies are relegated to the Appendix. In Appendix B there is a separate paper entitled "Supercritical Gaseous Discharge with High-Frequency Oscillations." This important paper forms the backbone for the analysis of the effects of nozzle and nozzle shape on the longitudinal screaming oscillations.

Because analytical results are a consequence of the assumptions made to obtain them, the assumptions of this analysis must be examined critically before the results are applied *per se* to a specific rocket operating condition. This statement merely emphasizes the fact that, because combustion mechanisms are obscure and critical experimental data scant, the authors of the book have been obliged to hypothesize a model to simulate the rocket combustion system. The boldest assumption made was to replace the very complex combustion reaction path with a parameter called the combustion time (or space) lag. Precedent for the use of such a mathematical artifice is to be found in several prior analyses. Crocco and Cheng consider the combustion time lag to comprise two parts, one insensitive to the processes in the chamber and the other sensitive to chamber conditions. A number of conditions may affect the sensitive portion of the combustion time lag; this analysis assumes that all these may be represented as a power of the local chamber pressure. Whether this procedure is valid may soon be ascertained by measurements of the combustion time delay; some of this work is being done at Princeton University under Professor Crocco's tutelage.

Without the intention of appearing hypercritical the reviewer would like to point out certain limitations of the work. For one, the mathematics are set up in terms of linear oscillatory systems; that is, the stability of a system subjected to a very small disturbance is the only one examined. This rules out oscillations that require a certain initial disturbance amplitude to grow. The possibility that these nonlinear systems may be important is discussed by the authors. Second, for the screaming (high-frequency) oscillations only longitudinal pressure waves are treated. Combustion-driven oscillations of the transverse type have been observed in large-scale rocket engines. The authors state that the transverse oscillations can occur only if combined with longitudinal modes; that is, no pure transverse modes can exist. Their statements also suggest that the case of combined longitudinal and transverse modes will be analyzed at a future date. Third, because the analysis assumes a fixed distribution of the combustion—a series of different distributions is considered, one at a time—and because only very small oscillations are considered, one factor which may be important in combustion rate processes, particularly for large oscillations, disappears. The missing factor is the extent of reaction. An additional parameter in the form $dN/dt \propto N$, where N is the unreacted propellant concentration, would be consistent with chemical rate formulations. This factor would cause the combustion rate to tail off as the propellant is consumed and would also have the effect of limiting the strength of the oscillations.

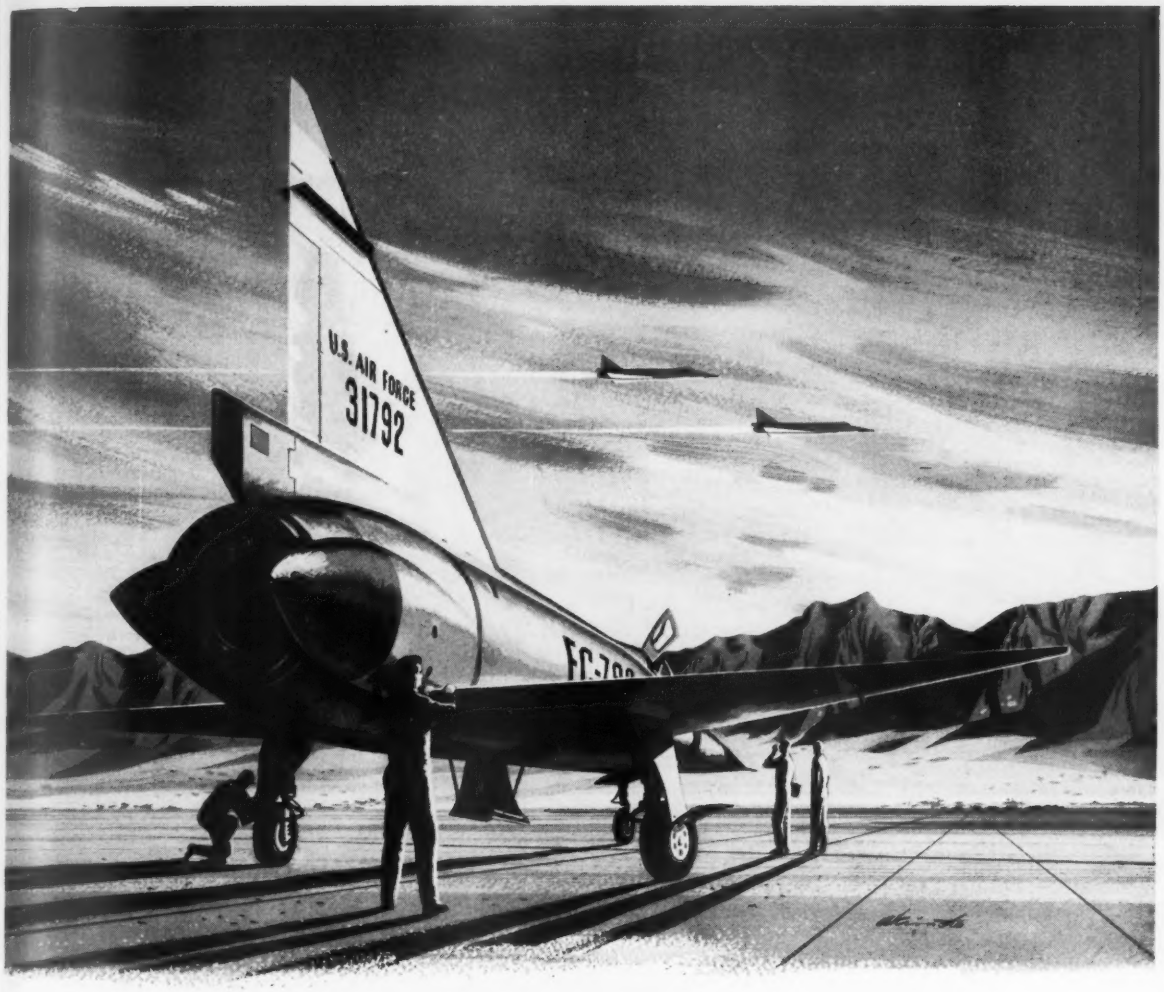
The words chosen to express an idea occasionally show bias in favor of the point of view being developed. An example: "It is therefore clear that the level of pressure fluctuation is not an objective index for the discrimination between stable and unstable combustion, and therefore between safe and dangerous conditions." The last part of this sentence is the questionable part. Those who have seen rocket chambers open up because of a single strong pressure surge would argue that pressure excursion is a damage criterion. The damage from oscillatory operation, on the other hand, probably results from metal fatigue or excessive heat transfer caused by the repetitive effect of the oscillations. If one cycle of this oscillation could be separated from the rest and passed through the chamber it is probable that no damage would ensue. This, perhaps, is the thought the authors wished to convey. An inference that pressure fluctuations are safe because they are not oscillatory would certainly be incorrect.

The considerable value of this book lies in the fact that it sets up a framework in which to try to fit experimental data. As new data become available, the present hypothesis may require modifications. For the present, it represents the most complete analytical treatment of the problems of oscillatory combustion in rocket engines to be found under one cover.

Book Notices

The Aircraft Year Book 1955, Edited by F. Hamlin and E. T. Miller, Lincoln Press, Inc., Washington, D. C., 1956,

(Continued on page 1147)



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Combustion

Detonation of Nitromethane, by G. Nahmani and Y. Manheimer, *J. Chem. Phys.*, vol. 24, May 1956, pp. 1074–1077.

The Explosive Oxidation of Diborane, by Walter Roth and Walter H. Bauer, *J. Phys. Chem.*, vol. 60, May 1956, pp. 639–641.

Evaluation of Fuel Characteristics in Thermojet Engine Combustion Processes, by George D. Kittredge, Progress Report 5, Dec. 1954–Jan. 1955. *Phillips Petroleum Co. Rep.* 1033–55R, Feb. 1955, 34 pp.

Flammability Limits of Hydrogen from 100-760 mm. Mercury Pressure and the Effect of Three Halogenated Hydrocarbons on the Flammability Limits of Hydrogen AD 500 and 760 mm. Mercury Pressure, by George J. Esseff and Kenneth P. Quinlan, *Ft. Belvoir Va. Engr. Res. Dev. Labs. Rep.* 1410, June 3, 1955, 48 pp.

A Study of the Absorption Spectra and Ignition Limits of Exploding Mixtures of Carbon Disulfide and Oxygen, by Albert L. Myerson, Francis R. Taylor, Philip L. Hanst, and Donald H. Tevethan, *Wright Air Dev. Center Tech. Rep.* 54–377, March 1956, 107 pp.

Mechanics and Kinetics of the Reaction Between Fuming Nitric Acid and/or Its Decomposition Products and Gaseous Hydrocarbons, *Franklin Inst. Labs. for Res. and Dev. Quart. Progress Rep.* Q-2542-5, Jan.–March 1956, 13 pp.

Performance Investigation of Can-Type Combustor. II. Water Injection at Various Stations in Combustor, by William P. Cook and Eugene V. Zettle, *NACA RM* E8F28, Sept. 30, 1948, 27 pp. (Declassified from Confidential, *NACA Research Abstracts* no. 102, June 22, 1956, p. 15.)

Consideration for the Attainment of a Standing Detonation Wave, by J. Rutkowski and J. A. Nicholls, *Michigan Univ. Engng. Res. Inst. Rep.* 2284-5-T Sept. 1955, 24 pp. (*AF Off. Sci. Res.* TN-55-216).

An Extension of the Theory of Thermal Explosion and Its Application to the Oscillatory Burning of Explosives, by D. M. Clemmow and J. D. Huffington, *Gt. Brit. Roy. Aircr. Estab., TN* RPD, 128, Sept. 1955, 28 pp.; *Trans. Faraday Soc.*, vol. 52, March 1956, pp. 385–396.

Values of Thermodynamic Functions to 12,000°K for Several Substances, by W. Fickett and Robert D. Cowan, *Atomic Energy Comm. Rep.* LA-1727, Sept. 1954, 21 pp.

Critical Considerations in the Measurement of Burning Velocities of Bunsen Burner Flames and Interpretation of the Pressure Effect. Measurements and Calculations for Methane, by W. H. Clingman and Robert N. Pease, *J. Amer. Chem. Soc.*, vol. 78, May 5, 1956, pp. 1775–1780.

The Combustion of Liquid-Fuel Spray, by J. A. Bolt and T. A. Boyle, *Trans. ASME*, vol. 78, April 1956, pp. 609–615.

The Influence of Methyl Bromide on Flames. Part 2, Diffusion Flames, by R. F. Simmons and H. G. Wolfhard, *Trans. Faraday Soc.*, vol. 52, Jan. 1956, pp. 53–58.

The Slow Oxidation of Methane, by Alfred Egerton, G. J. Minkoff, and K. C. Salooja, *Proc. Roy. Soc.*, vol. A235, April 24, 1956, pp. 158–173.

Effect of Radioactivity and Corona Discharge on Flame Stabilization, by Morton Mitchner and Robert A. Gross, *J. Aeron. Sci.*, vol. 23, June 1956, pp. 607–608.

The Shadowgraph of a Flat Flame, by F. J. Weinberg, *Proc. Roy. Soc.*, vol. A235, June 12, 1956, pp. 510–517.

Surface Activity at the Organic-Liquid/Air Interface, by A. H. Ellison and W. A. Zisman, *Naval Res. Lab. Rep.* 4684, Feb. 3, 1956, 21 pp.

Mechanism of Detonation, by M. A. Cook, R. T. Keyes, and A. S. Filler, *Trans. Faraday Soc.*, vol. 52, March 1956, pp. 369–384.

Studies on the Flame Spectrochemical analysis. II. Determination of Microamount of Calcium and Magnesium, by S. Ikeda, *Sci. Rep. Res. Inst. Tohoku Univ.*, vol. 8A, Dec. 1955, pp. 575–582.

Concerning the Absolute Rates of Reactions in Flames, by A. S. Rozlovskii, *J. Phys. Chem. USSR*, vol. 30, no. 2, 1956, pp. 251–260 (in Russian, with summary in English).

Studies on the Flame Spectrochemical Analysis. III, by S. Ikeda, *Sci. Rep. Res. Inst. Tohoku Univ.*, vol. 8A, Feb. 1956, pp. 8–13.

Spectral Absorption Method for Determining Population "Temperatures" of Hot Gases, *J. Optical Soc. Amer.*, vol. 46, April 1946, pp. 246–254.

A Kinetic Study of the Reaction of Decaborane with Alcohols, by H. C. Beachell and T. R. Meeker, *J. Amer. Chem. Soc.*, vol. 78, May 5, 1956, pp. 1796–1800.

The Decomposition of Ozone in Aqueous Solution, by Mary L. Kilpatrick, Claude C. Herrick, and Martin Kilpatrick, *J. Amer. Chem. Soc.*, vol. 78, May 5, 1956, pp. 1784–1789.

The Thermal Decomposition of Ethyl Nitrate, by F. H. Pollard, H. S. B. Marshall, and A. E. Pedler, *Trans. Faraday Soc.*, vol. 52, Jan. 1956, pp. 59–68.

Researches on the Oxidation and Auto-Ignition of Paraffinic Hydrocarbons in the Gaseous Phase; Mixtures of Normal Hexane and Air, by E. Fréling, *Inst. Francais Petrole Rev. Ann. Combustibles Liquides*, vol. 11, Jan. 1956, pp. 134–157, 253 references (in French).

Polarographic Determination of Alkyl Phthalate Esters in Cordite and Double Base Propellants, by Gerald D. Whitnack, Robert D. Weaver, and E. St. Clair Gantz, *Navord Rep.* 5022 (NOTS 1361), March 1956, 11 pp.

A Comparison of Three Methods for the Analysis of Gaseous Ozone, by Clarence C. Shubert, S. J. Garvin, and David Garvin, *Project Squid Tech. Rep.* PR-63-P, March 1956, 7 pp.

The Thermal Decomposition of Diol Nitrates. Part III, by Lester P. Kuhn, Robert Wright, and Louis de Angelis, *Aberdeen Proving Ground Ballistic Res. Labs. Mem. Rep.* 985, March 1956, 13 pp.

Performance of Certain Composite Charges in the 105-mm. Howitzer, by F. Yagi and W. C. Taylor, *Aberdeen Proving Ground Ballistic Res. Labs. Mem. Rep.* 992, April 1956, 73 pp.

Heat Transfer and Fluid Flow

The Accelerated Motion of Droplets and Bubbles, by T. Pearcey and G. W. Hill, *Australian J. Phys.*, vol. 9, March 1956, pp. 19–30.

A Common Basis for the Correlation of Forced and Natural Convection in Horizontal Cylinders, by Robert Lemlich and Ronald Hoke, *J. Amer. Inst. Chem. Engrs.*, vol. 2, June 1956, pp. 249–250.

A Semiempirical Solution for Local Heat Transfer Coefficients for Flow in Nonparallel Passageways, by P. N. Stevens and E. F. Obert, *J. Amer. Inst. Chem. Engrs.*, vol. 2, June 1956, pp. 271–272.

Flow Distribution Along Parallel Heated Channels, by A. R. Gruber and S. C. Hyman, *J. Amer. Inst. Chem. Engrs.*, vol. 2, June 1956, pp. 199–205.

The Flow of a Viscous Liquid in a Circular Tube Under Pressure Gradients Varying Exponentially With Time, by Lakshmi Sanyal, *Indian J. Phys.*, vol. 30, Feb. 1956, pp. 57–61.

Preliminary Investigation of Compressor Blade Vibration Excited by Rotating Stall, by Merle C. Huppert, Donald F. Johnson, and Eleanor L. Costilow, *NACA RM* E52J15, Dec. 1952, 27 pp. (Declassified from Confidential, *NACA Research Abstracts* no. 102, June 22, 1956, p. 16.)

Two- and Three-Dimensional Flow of Air Through Square-Edged Sonic Orifices, by Alexander Weir, Jr., J. L. York, and R. B. Morrison, *Trans. ASME*, vol. 78, April 1956, pp. 481–488.

On the Theory of Discharge Coefficients for Rounded-Entrance Flowmeters and Venturis, by M. A. Rivas, Jr., and A. H. Shapiro, *Trans. ASME*, vol. 78, April 1956, pp. 489–497.

A Survey of Aerodynamic Excitation Problems in Turbomachines, by A. Sabatiuk and F. Sisto, *Trans. ASME*, vol. 78, April 1956, pp. 555–564.

The Flow in a Vee-Gutter Cascade, by W. G. Cornell, *Trans. ASME*, vol. 78, April 1956, pp. 573–580.

Heat Transfer in Chemically Reacting Gas Mixtures, by Joseph O. Hirschfelder, *Wisconsin Univ. Naval Res. Lab. Rep.* WIS-ONR-18, Feb. 6, 1956, 28 pp.

Some Aerodynamic Investigations in Centrifugal Impellers, by J. T. Hamrick, *Trans. ASME*, vol. 78, April 1956, pp. 591–602.

A New Electrical Analog Method for the Solution of Transient Heat-Conduction Problems, by G. Liebmann, *Trans. ASME*, vol. 78, April 1956, pp. 655–665.

Heat Conductivity in Polyatomic or Electronically Excited Gases, by Joseph O. Hirschfelder, *Wisconsin Univ. Nav. Res. Lab., Rep.* WIS-ONR-22, April 1956, 14 pp.

Instrumentation

Procedures for Performing and Evaluating Acoustical Surveys of Turbojet Engine Test Facilities, by Samuel Labate (Bolt, Beranek and Newman, Inc.), *Wright Air Dev. Center Tech. Rep.* 55–145, April 1955, 52 pp.

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tion of Jet Engine Test Cells, by Samuel Labate (Bolt, Beranek and Newman, Inc.), *Wright Air Dev. Center Tech. Rep.* 55–115, April 1955, 132 pp.

Experimental Determination of Combustion Temperatures of Ammonium Perchlorate Rocket Propellants, by Dwight A. Mahaffy, *Princeton Univ. Dept. Aeron. Engng. Rep.* 324, Sept. 1955, 78 pp. (Thesis, M.S.E.)

Terrestial Flight, Vehicle Design

Missile Guidance by Three-Dimensional Proportional Navigation, by Fred P. Adler, *J. Appl. Phys.*, vol. 27, May 1956, pp. 500–507.

The Ballistic Missile, by Mark S. Watson, *Ordnance*, vol. 40, May-June 1956, pp. 948–952.

New Guided Missiles, *Ordnance*, vol. 40, May-June 1956, p. 957.

Table of Soviet Missiles, by Alfred J. Zaehringer, *J. Space Flight*, vol. 8, May 1956, pp. 1–4.

Determination of the Direction of Flight of a Missile by Ground Observations, by Oswald Wyler, *Holloman Air Dev. Center Rep.* HADC TR-56-4, Feb. 1956, 19 pp.

Orientation of Fixed Camera for Maximum Coverage of Space Trajectory, by W. J. Berger, RCA Data Reduction Report 24, *AF Missile Test Center TN* 55–50, Sept. 13, 1955, 13 pp.

Possibilities of a Missile in Vertical Flight, by C. Casci, *L'Aerotecnica*, vol. 36, Feb. 1956, pp. 27–36 (in Italian).

Some Recent Aerodynamic Techniques in Design of Fin-Stabilized Free-Flight Missiles for Minimum Dispersion, by M. W. Hunter, A. Shef, and D. V. Black, *J. Aeron. Sci.*, vol. 23, June 1956, pp. 571–577.

Accessory Turbine (Table), *Aviation Age*, vol. 25, June 1956, pp. D-20–D-21.

Atomic Energy

A Bibliography of Available Digital Computer Codes for Nuclear Reactor Problems, by A. Radkowsky and R. Brodsky, *Atomic Energy Comm.* AECU-3078, Oct. 1955, 102 pp.

Reactor Heat Transfer Information Meeting Held at Brookhaven National Laboratory, Oct. 18–19, 1954. *Atomic Energy Comm.* BNL-2446, Dec. 1955, 194 pp.

Reaction Rates of Non-Isothermal Processes. I. A Simple Model for First Order Kinetics, by W. Davis, Jr., *Atomic Energy Comm.* K-1243, Nov. 1955, 27 pp.

Kinetics Calculations for Homogeneous Reactors, by W. C. Sangren, *Atomic Energy Comm.* ORNL 1205, April 1952, 89 pp.

High Pressure Design for Studies of Reactions Between Heated Metals and High Temperature Water, by D. C. Kaulitz and J. E. Minor, *Atomic Energy Comm.* HW-38876, Sept. 1955, 21 pp.

Automotive Nuclear Heat Engines and Associated High-Temperature Materials, by F. L. Schwartz and H. A. Ohlgren, *SAE Prepr.*, June 3–8, 1956, 46 pp.

Small Liquid Metal Fueled Reactor Systems, by Jack Chernick, *Nuclear Sci. Engng.*, vol. 1, May 1956, pp. 135–155.

A Preliminary Study of Superheating Boiling Reactors, by M. Treshow, *Nuclear Sci. Engng.*, vol. 1, May 1956, pp. 167–173.

Fuel Element Design, by C. E. Weber, *J. Metals*, vol. 8, May 1956, Sect. 1, pp. 651–659.

Ceramic Fuel Materials for Nuclear Reactors, by J. R. Johnson, *J. Metals*, vol. 8, May 1956, Section 1, pp. 660–664.

Atomic Power for British Aircraft, *Atomics*, vol. 7, May 1956, pp. 173–174.

Thermal Conductivity and Heat Capacity of Molten Materials. Part 6. The Thermal Condictivity of Betyllium Oxide from 40° to 750°C, by D. A. Ditmars and D. C. Ginnings, *Wright Air Dev. Center Tech. Rep.* 53–201, Part 6, Oct. 1955, 18 pp.

Fuels, Propellants, and Materials

Design, Fabrication and Testing of a Titanium Shroud for Jet Engines, by D. Root, *North Amer. Aviation Inc. Rep.* NA-55-815, July 14, 1955, 43 pp.

Diffusion Coefficients in Hydrocarbon Systems: n-Heptane in the Gas Phase of the Ethane–n-Heptane and Propane–n-Heptane Systems, by L. T. Carmichael and B. H. Sage, *J. Amer. Inst. Chem. Engrs.*, vol. 2, June 1956, pp. 273–276.

Analysis of Spherical Pressure Vessel Having an Energy Source Within the Wall, by R. H. Chapman, *Atomic Energy Comm.* ORNL-0987, Oct. 1954, 112 pp.

Effect of Rapid Heating and Cooling on the Hardness and Strength of 2014-T6 and 7075-T6 Aluminum Alloys, by W. K. Smith, *Navord Rep.* 5065, (NOTS 1420), April 1956, 7 pp.

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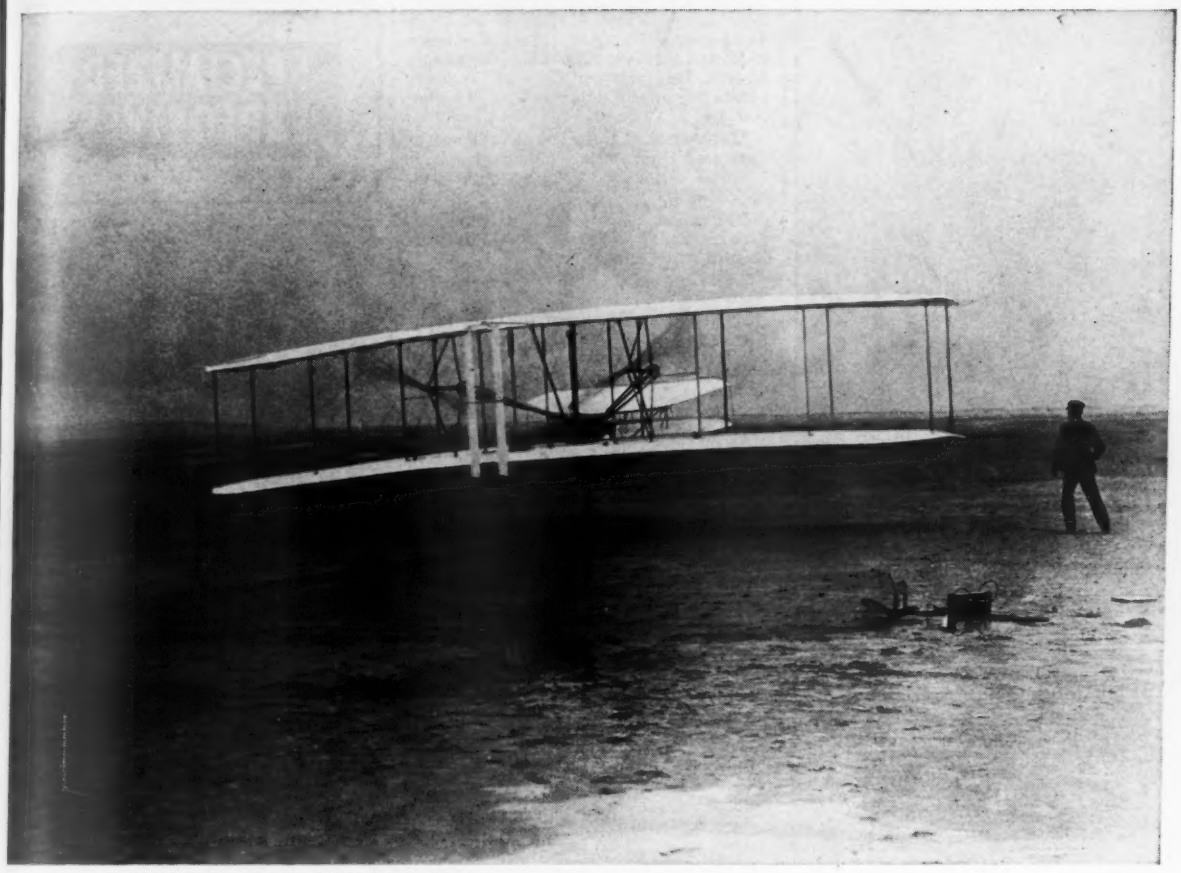

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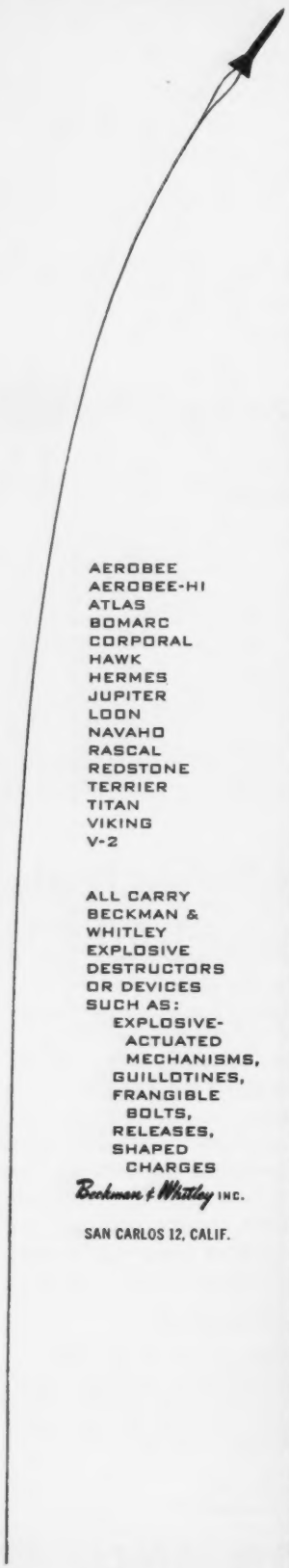

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Mechanism of Electrical Breakdown in Saturated Hydrocarbon Liquids, by T. J. Lewis, *J. Appl. Phys.*, vol. 27, June 1956, pp. 645–650.

Evaluation of Corporal and Nike Propellants and Propellant Containers with Regard to Storage. Part 1, *White Sands Proving Ground, Tech. Mem.* 316, March 1956, 31 pp.

Application of Radioisotope Tracer Techniques to the Investigation of Interaction of Zinc and Jet Fuel, by B. L. Gilbert and J. L. Kalinsky, Final Technical Report, *New York Naval Shipyard Material Lab.*, Dec. 23, 1955, 30 pp.

Boron, Boron Hydrides, and Related Substances—a Bibliography, by Mary E. Schroder and Thomas C. Goodwin, Jr., Parts 1 and 2, *Lib. Congress*, June and April 1955, 178 and 98 pp.

Starting of Rocket Engine at Conditions of Simulated Altitude Using Crude Monoethylanaline and Other Fuels with Mixed Acid, by Dezso J. Ladanyi, John L. Sloop, Jack C. Humphrey, and Gerald Morrell, *NACA RM* E50D20, July 19, 1950, 64 pp. (Declassified from Confidential, *NACA Research Abstracts* no. 102, June 22, 1956, p. 15.)

Low Temperature Ignition Delay Characteristics of Several Rocket Fuels with Mixed Acid in Modified Open Cup Apparatus, by Riley O. Miller, *NACA RM* E50H16, Oct. 17, 23 pp. (Declassified from Confidential, *NACA Research Abstracts* no. 102, June 22, 1956, p 15.)

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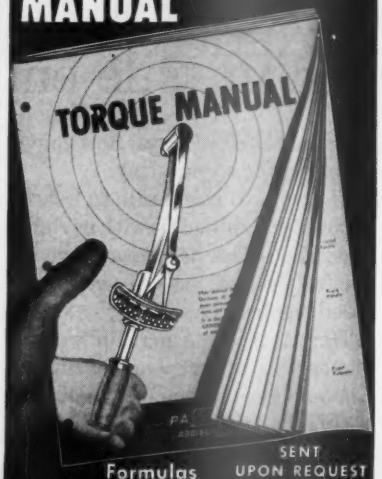

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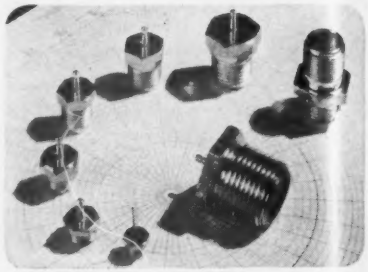

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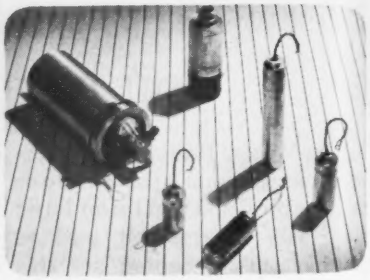

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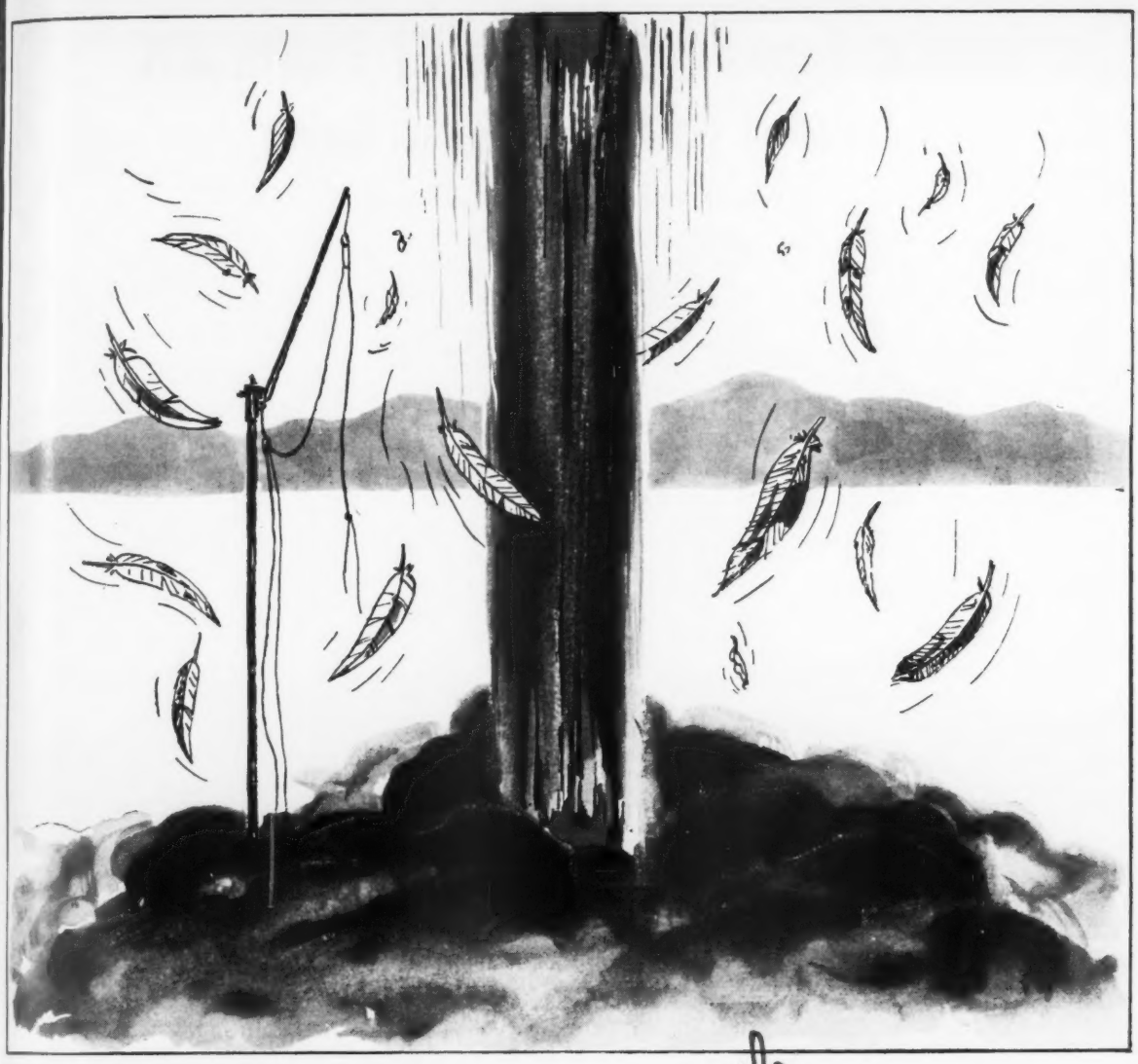

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479 pp. $6. This book is an official publication of the Aircraft Industries Association of America, Inc. It is a compilation of statistics and multifareous information concerning the aircraft industry. It summarizes the activities of companies actively engaged in the production of frames and engines. In other chapters it discusses research and development, guided missiles, government agencies, and airlines. Detailed information concerning the planes in production is outlined. Other material of interest includes chronologies, addresses, records, etc.

Guide to the Stars, by Hector MacPherson, Revised Edit., 1955, Philosophical Library, New York, 144 + ix pp. $2.75. This little book includes both text material and a number of plates. According to the author it is written to provide a brief discussion of the important astronomical discoveries in the past as well as a modern description of the Universe. The author anticipates that the laymen will be able to identify constellations and their more important stars.

New Equipment and Processes

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Product Literature

Explosion Chamber. For safe simulation of explosions up to altitudes of 80,000 ft. Tenney Engineering, 1090 Springfield Rd., Union, N. J.

Automatic Control for Aerodynamic Research. Bulletin MSP-133 details equipment for surge, altitude, mass flow, pressure, temperature, and position. Hogan Corp., Box 1346, Pittsburgh 30, Pa.

Combustible Gas Analysis. Data Sheet 10.45-46 describes Davis Gas Analyzers plus recorders and controllers. Minneapolis-Honeywell Regulator Co., Wayne & Windrim Ave., Philadelphia 44, Pa.

Anthropomorphic Test Dummies. Production Modular Series are described in brochure. Alderson Research Laboratories, 10 E. 38 St., New York 16, N. Y.

Fluid Pressure Cells. Bulletin 4306 gives specifications and applications of SR-4 units. Rocket test work is illustrated. Baldwin-Lima-Hamilton Corp., Philadelphia 42, Pa.

Hydrogen Peroxide. Safety data booklet SD-53 tells how to safely handle and use peroxide along with storage, shipping, disposal, and health hazards. Manufacturing Chemists' Association, 1625 Eye St., N. W., Washington 6, D. C. $0.30.

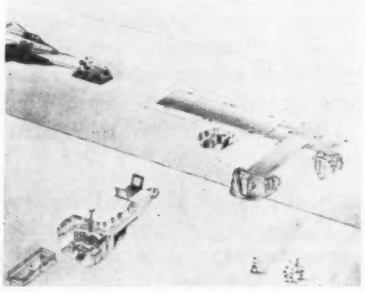
Safety. How to organize a safety program is treated in this 1341-page text. National Safety Council, 425 N. Michigan, Chicago, Ill. $13.50.

Laboratory Directory. 1956 Edition indexes laboratories by category and location. American Council of Independent Laboratories, 4302 East-West Highway, Washington 14, D. C.

Missile Data. Bulletin 55SD3 gives nose cone temp for V-2 flight. Bulletin R55AO515 summarizes "Bumper Project." General Electric Co., Schenectady 5, N. Y.

Jet Silencer. Dura-Stack system for noise control in ground run-up is discussed in this 12-page booklet. Industrial Acoustics Co., 341 Jackson Ave., New York 54, N. Y.

Thrust Stand. Brochure details jet aircraft and engine thrust stands. Bristol Engineering Corp., Bristol, Pa. (photo).



Environmental Test Equipment. Discusses line of equipment. Murphy & Miller, 1326 S. Michigan, Chicago, Ill.

Cosmic Ray Counters. Performance and specifications. Radiation Counter Laboratories, 5122 W. Grove, Skokie, Ill.

Electro-Optical. Instruments for process control are described in 8-page catalog. Barnes Engineering Co., 30 Commerce Rd., Stamford, Conn.

Gyros and Potentiometers. Vertical, rate, and directional gyros, miniature and sine-cosine potentiometers are tabulated. Gyromechanisms, Halesite, Long Island, N. Y.

Valves. Bulletin A5200:D describes airborne hydraulic valves. Vickers, Inc., 1400 Oakman, Detroit 32, Mich.

Pneumatic Disconnect. Data for models to 3000 psi. Eastern Aircraft Products Corp., 229 River St., Orange, N. J.

Organic Peroxides. Listing of 23 diacyl, diacyl acid, ketone, aldehyde, alkyl peroxides, peresters, and hydroperoxides. Lucidol Div., Wallace & Tiernan, 1700 Military Rd., Buffalo 5, N. Y.

Nitroparaffin Symposium. Sixty-page brochure gives properties, uses of nitroparaffins. Commercial Solvents Corp., 260 Madison Ave., New York 16, N. Y.

Heat Detector. Cells are described in Bulletin TDS-HCA. Servo Corp. of America, 20 Jericho Turnpike, New Hyde Park, N. Y.

Tapes. 25-page book gives properties, specs, applications for pressure-sensitive tapes. Behr-Manning, Norton Co., Troy, N. Y.

Moly Stress-Strain. Data for range of −196 to 1540 C. "Tensile Deformation of Molybdenum as a Function of Temperature and Strain Rate," PB 111815. Office of Technical Services, Dept. of Commerce, Washington D. C. $1.

Titanium Alloy Systems. Binary and ternary systems, crystal structures. "Constitution of Titanium Alloy Systems," PB 1115085. Office of Technical Services, Dept. of Commerce, Washington, D. C. $4.

Thermocouple Equivalents. Millivolt-temperature table. Bulletin F7255. Barber-Coleman Co., Wheelco Instruments Div., Rockford, Ill.

Silicones. New 1956 guide lists 150 widely used silicones. Dow Corning Corp., Midland, Mich.

Fiberglas. Technical folder "Fiberglas Reinforced Molding Compounds" gives listing of manufacturers, applications, and materials. Owens-Corning Fiberglas Corp., 598 Madison Ave., New York 22, N. Y.

Non-Metallic Pump Impellers. Surveys synthetic rubbers, fluocarbons, laminates for use in chemical handling. Eco Engineering Co., 12 New York Ave., Newark, N. J.

Universal Testing Machines. Baldwin-Tate-Emery line are described in Bulletin 4401. Models range from 10,000 to 5,000,000 lb. Baldwin-Lima-Hamilton Corp., Testing Equipment Dept., Philadelphia 42, Pa.

Selenium Photocells and Sun Batteries. 58 pages; 35 illustrations, charts, and diagrams for engineers and experimenters. International Rectifier Corp., Product Information Dept., 1521 E. Grand Ave., El Segundo, Calif. $1.50.

Alternating Flow of Fluid in Tubes. Instrument Notes no. 30 is 8-page illustrated book on parallel plates, circular and rectangular tubes. Statham Laboratories, Inc., 12401 W. Olympic Blvd., Los Angeles 64, Calif.

Powder Metallurgy Bibliography. List of 250 articles printed during 1954 and 1955. Harper Electric Furnace Corp., 39 River St., Buffalo 2, N. Y.

Fail-Safe System Design. 8-page booklet describes monitoring output of operating systems. Electronics Div., Scully Signal Co., Melrose, Mass.

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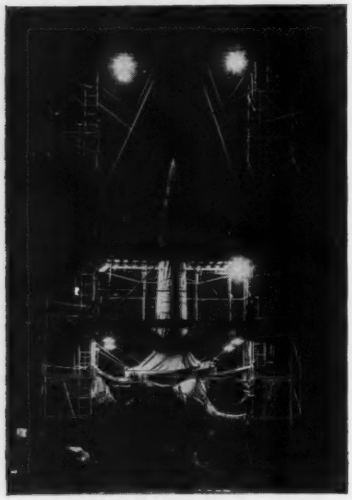
How We're Doing It...

The Department's primary objective is to create the country's TOP TEAM on Guided Missile Research and Development and with this team assume FULL MISSILE SYSTEM RESPONSIBILITY for the entire General Electric Company. This will involve making use of the tremendous potential in the company's more than 100 operating departments and its many research laboratories.



ZERO minus 4 hours! A G-E test missile, still shrouded in the early morning dampness before launching, represents more than a decade of research and development.

Where We're Headed...

INTO EVERY PHASE OF MISSILE RESEARCH & DEVELOPMENT including:

...MISSILE WEAPONS SYSTEMS—target and missile tracking—radars—computers—handling equipment—launching equipment—logistics equipment—and others, all designed FROM THE GROUND UP as one system!

...SPECIFIC MISSILES—also Satellites including propulsion, guidance, airframes, and warhead arming and fuzing devices.

...SPECIAL COMPONENTS OF MISSILES—such as inertial guidance systems.

What We're Using...

HYPERSONIC WIND, SHOCK, HELIUM TUNNELS—mass accelerators—linear accelerators—electric arc mass accelerators—hyper-velocity shock tunnels. UNDER DEVELOPMENT: the LARGEST GAS SHOCK TUNNEL in the country...PLUS laboratories and equipment second to none. AND WHEN NEEDED—the resources of over 100 other G-E departments!

What All This Means to You...

Stable career growth, full use of your abilities, creative experience and rapid advancement either into management or further specialization, with a profesional staff that is expanding rapidly.

Scientists with advanced degrees will have a particularly attractive opportunity to engage in high levels of basic and applied research in such advanced fields as Astrophysics, High Temperature Phenomena, Advanced Mathematical Concepts, Aerodynamics, Classical Physics, Materials Development, and Communications Theory.

...Engineers and Scientists with education and experience in any of the fields listed below are invited to correspond with us...

DEGREE: *Electrical Engineer, Aeronautical Engineer, Aerodynamics, Mechanical Engineer, Physics, Mathematics.*

EXPERIENCE: SYSTEMS—*Development, Synthesis, Operations Analysis* • AEROPHYSICS • COMPUTER DESIGN—*Analogue, Digital* • MATERIALS & PROCESSES • INSTRUMENTATION—*Telemetry, Transducers, Recording, Recovery* • DATA PROCESSING—*Systems Design, Analysis, Programming* • GUIDANCE—*Intertial Guidance, Component Development* • TECHNICAL WRITING • FIRE CONTROL • STRUCTURES—*Thermodynamics, Electrical Design, Stress Analysis, Structure Design, Vibration, Aerodynamics* • ARMING AND FUZING—*Component Development, Test Equipment* • FIELD TEST • SYSTEMS TEST • GROUND SUPPORT EQUIPMENT DESIGN—*Controls, Handling Equipment, Launching Equipment.*

Missile & Ordnance Systems Department would be pleased to receive a resume of your education and experience.

All resumes will be carefully reviewed by the MANAGERS of our various technical components. You will be invited to visit our offices and discuss the work we are doing directly with the manager with whom you would be working. All communications will be entirely confidential. (You need not reveal the name of your present employer.)

Please send resume to Mr. John Watt, Room 510-8
MISSILE & ORDNANCE SYSTEMS DEPARTMENT

GENERAL ELECTRIC

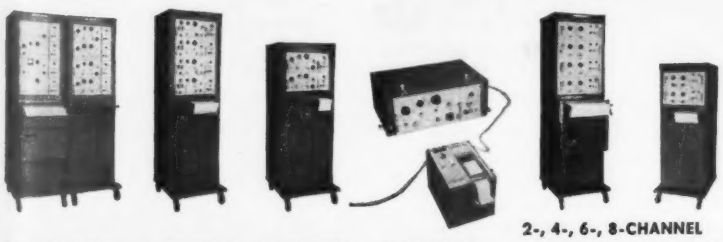
3198 Chestnut Street • Philadelphia, Pennsylvania

SIGHTS of rockets swooshing heavenward become more and more familiar as we thumb through today's industrial publications. The recalcitrant rocket shown on this page indicates that things *can* go wrong in research, and we don't claim that the absence of a Sanborn oscillographic recording system somewhere along the line was the reason for this disappointing trajectory.

What we do wish to say is that Sanborn equipment is playing an increasingly vital part in rocket development. Used in the laboratory to record flight behavior simulated by analog computers, and in plotting rooms at testing bases to tape down telemetered data, Sanborn "150's" are helping rockets to get and stay where they belong.

You can see Sanborn systems in many other places, too. Oil fields, electronic component production lines, machine tool plants, hydraulic testing laboratories, numerous aircraft manufacturers, computing facilities . . . are putting single to 8-channel Sanborn systems to work. (Most are housed in vertical mobile cabinets, while those in the "field" are often divided into portable packages for each instrument.) All of them give their users inkless, permanent recordings in true rectangular coordinates, one percent linearity, as many as nine chart speeds, and the efficiency (and economy) inherent in Sanborn unitized design. A dozen different plug-in preamps further extend their value, by making changeover to new recording inputs a quick and easy procedure.

SANBORN COMPANY
CAMBRIDGE 39, MASSACHUSETTS



8-, 6-CHANNEL 4-CHANNEL 2-CHANNEL 1-CHANNEL

2-, 4-, 6-, 8-CHANNEL ANALOG COMPUTER SYSTEMS

Which way rockets are going may not be a primary concern of yours. But if recording problems *are*, you're apt to find some interesting and useful answers in Sanborn's 16 page "150 System" catalog. Write to us for a copy.

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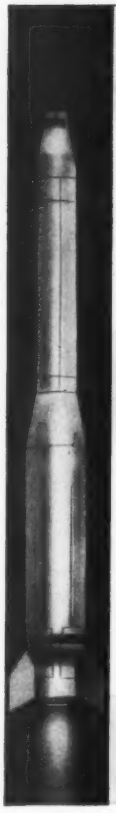


"LIFE INSURANCE" The preservation of the peace and security of this nation depends upon two things: Our diplomatic wisdom in a troubled world, and the power to protect ourselves if peaceful negotiation should fail.

Point 2 is part of *our* responsibility. This is the Martin-U.S. Air Force TITAN program... one of the most advanced and critically important development projects in America today... an Inter-Continental Ballistic Missile conceived in peace and dedicated to the proposition that no aggressor shall ever take the life of this country.

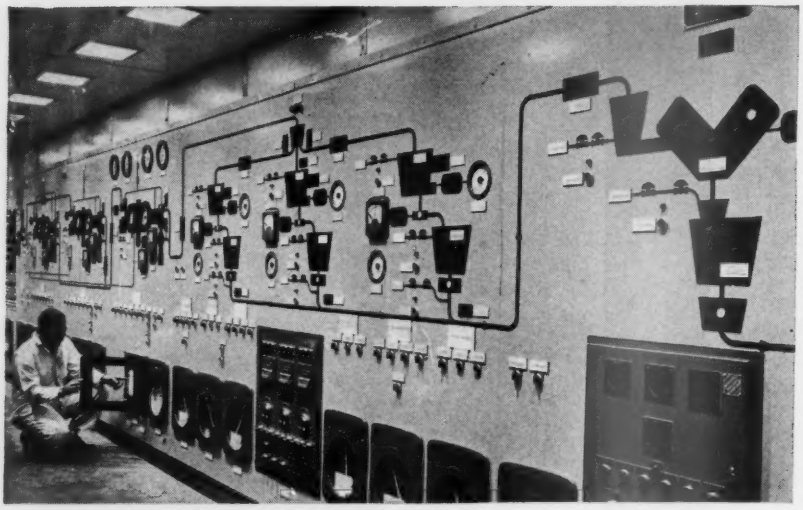
MARTIN

BALTIMORE · DENVER

PHILLIPS OPERATES

"TEXAS SIZE" FACILITIES

FOR DEVELOPMENT AND MANUFACTURE OF ROCKETS



Air Force Plant 66 near McGregor, Texas, operated by Phillips Petroleum Company, has facilities for applied research, development, test and manufacture of solid propellant rockets. Phillips family of rocket propellants—made from common petroleum-derived materials such as ammonium nitrate, synthetic rubber and carbon black—are being used in rocket motors for JATOs, large boosters, and in other applications.

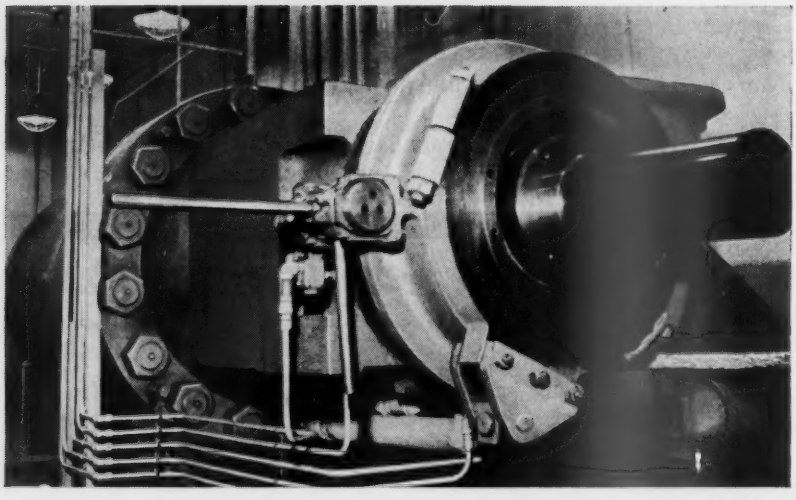
The Phillips family of solid propellants provides practical answers to many troublesome problems. For example, Phillips ammonium nitrate type propellants operate successfully from −75 to 170 F . . . can be stored for long periods of time . . . have exhaust gases that are noncorrosive and relatively low in temperature.

Can our staff of experienced scientists and engineers help you in solving problems in propulsion systems, primary rockets, booster rockets and other related matters? We invite you to discuss your technical and production problems with us.

ABOVE ◂ Process and inspection controls, from mixing to final extrusion of Phillips solid propellants, maintain high standards of quality.

◂LEFT, Readily available petrochemicals are combined to make new *low cost* propellants.

BELOW ◂ Giant extruders form solid propellants that are easily handled and can be stored for long periods.



PHILLIPS PETROLEUM COMPANY

Bartlesville, Oklahoma

Address all inquiries to:
Rocket Fuels Division, McGregor, Texas

Phillips 66

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